RI051289D

DRAFT
TECHNICAL MEMORANDUM

MODEL SIMULATION OF FLOW, SUSPENDED SEDIMENT, AND HEAVY METAL TRANSPORT FOR THE ABERJONA RIVER WATERSHED

REMEDIAL INVESTIGATION /FEASIBILITY STUDY

INDUSTRI-PLEX SITE
WOBURN, MASSACHUSETTS

RESPONSE ACTION CONTRACT (RAC), REGION I

For
U.S. Environmental Protection Agency

By
Tetra Tech NUS, Inc.

EPA Contract No. 68-W6-0045
EPA Work Assignment No. 116-RICO-0107
TtNUS Project No. GN4123

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A Model Review by Watermark Inc.

LIST OF ACRONYMS

As	Arsenic
AWM	Aberjona Watershed Model
CC	Composite Concentrations
Cr	Chromium
Cu	Copper
Diff.	Difference
EPA	Environmental Protection Agency
Fe	Iron
FEMA	Federal Emergency Management Agency
FS	Feasibility Study
GIS	Geographic Information System
HBHA	Halls Brook Holding Area
Hg	Mercury
ISRT	Industri-plex Site Remedial Trust
MSGRP	Multiple Source Groundwater Response Plan
Meas.	Measured
MIT	Massachusetts Institute of Technology
Mod.	Modeled
NCDC	National Climatic Data Center
MWRA	Massachusetts Water Resources Authority
Pb	Lead
RI	Remedial Investigation
TSS	Total Suspended Solids

LIST OF ACRONYMS (cont.)

TtNUS	Tetra Tech NUS, Inc.
USGS	United States Geological Survey
USEPA	U.S. Environmental Protection Agency

UNITS OF MEASURE

percent	Percent, parts per hundred
cm	Centimeter
cfs	Cubic feet per second
^{o}C	Degrees Celsius
ft	Feet
gpd	Gallons per day
g/hr	Grams per hour
km	Kilometer
NTU	Nephelometric turbidity units
µg/L	Micrograms per liter
uS/cm	microSiemens per centimeter (unit of conductivity)
mi	Mile
mg	Milligrams
mg/L	Miligrams per liter
mgd	Million gallons per day
mg/kg	Mg of metal per kg of soil
ml	Milliliter
mm	Millimeter
mV	Milivolts

E.0 EXECUTIVE SUMMARY

This report presents the development of a computer model for the Aberjona River Watershed which is capable of simulating sediment and metals transport throughout the river system. This report was prepared as part of the Industri-plex Superfund Site Multiple Source Groundwater Response Plan (MSGRP) Operable Unit 2 and including Wells G&H Superfund Site Aberjona River Study Operable Unit 3 (Study Area) located in Woburn, Massachusetts. This report was prepared by Tetra Tech NUS, Inc. for the United States Environmental Protection Agency (EPA) under Work Assignment No. 116-RICO-0107, Contract No. 68-W6-0045.

An extensive monitoring program was established throughout the watershed that included measurements of precipitation, streamflow, suspended sediment, and metals concentrations (dissolved and total), in addition to other physico-chemical parameters. The intensive monitoring period occurred during an 18-month time frame beginning May 2001 and ending October 2002. The measurements from this period were utilized to update and calibrate an existing computer code that was originally developed for the Aberjona River during the early 1990's. The primary updates to the code include the re-organization of the code to accommodate the geometry of the TtNUS network of 8 monitoring stations within the model domain, the addition of a component which accounts for water losses from the river as a function of depth, and the addition of two metals to the code, lead and mercury, in addition to the existing list that included arsenic, iron, chromium, and copper.

The updated computer code developed for this study accommodates the geometry of the TtNUS monitoring network by separating the watershed into a series of modules, each module corresponding to the surface area of the watershed that drains directly towards a particular monitoring station. Streamflow from each module within the watershed was modeled as the sum of three different flow components, a quick component associated with direct runoff and storm sewer inflows, a slow component which is a storm induced groundwater flow component, and longterm baseflow which represents the baseline groundwater input to the river. Dissolved metal fluxes were modeled by assigning each flow component a dissolved metal concentration. Sediments were assumed to be transported with each flow system. Sediment transport for the quick system was modeled through a build-up and wash-off mechanism. Slow and longterm baseflow sediments were modeled by a low but constant suspended sediment concentration. Once the sediments entered the channel, the model checked for possible deposition and erosion. Particulate metal fluxes were modeled by assigning each suspended sediment component a particulate metals concentration in units of mass of metal per mass of sediment.

The model was found to perform very well in simulating flow and dissolved metals transport when compared to actual measurements. Measures of performance included differences between mean measured and modeled values and evaluation of time series plots. For flow, additional measures of performance included the goodness of fit (R^2), percentile flows, and histogram plots. Overall, the flow portion of the model performed extremely with mean measured and modeled flow within 10 percent for 5 of the 8 station and within 20 percent for the remaining three stations. The R^2 values between measured and modeled values were upwards of 0.7 indicating a good fit. Suspended sediment concentrations and fluxes were modeled well with 15 percent of the measured mean concentration with the exception of Station 2 composite suspended sediment concentrations which were over-estimated by about 30 percent. Total modeled arsenic concentrations were within 1 microgram per liter (µg/L) of the mean measured values except for Station 6 where they were within 6 µg/L, and Stations 4 and 7 where they were over-estimated by 13 µg/L. The discrepancies in the arsenic concentrations were due to measured losses in the river over and beyond dilution effects.

Overall the model predicts that the majority of the water entering the Aberjona River comes from the longterm baseflow component (i.e. groundwater). Suspended sediment transport from the watershed is estimated at 54 kilograms per hour (kg/hr) on average with the majority originating from the quick flow system or from the erosion of sediments that were previously deposited within the channel. Total metals transport at the outlet of the river was estimated at 30 grams per hour (g/hr), 7000 g/hr, 34 g/hr, 81 g/hr, 63 g/hr, 0.8 g/hr for arsenic, iron, chromium, copper, lead, and mercury, respectively. According to the model, over 70 percent of the arsenic observed in the river originates within Module 2 which is located in the northern part of the watershed and represents the drainage area contributing to the Halls Brook Holding Area. As a result the largest normalized arsenic fluxes (up to 30 g/hr per square mile) originated from this module.

Once calibrated the model was then modified to account for two primary groundwater remediation scenarios including a reactive wall and a cofferdam scenario which was evaluated using three different sets of values to provide bounds on expected metals removals from the system attributed to contaminated groundwater discharges. Overall, the predictions for “optimum cofferdam” and “reactive wall” scenario were very similar. These scenarios simulate reductions in total arsenic flux at Stations 2 and 4 by as much as 90 percent (from 9 to 15 g/hr to 1 or 2 g/hr). This translates to about a 25 percent reduction in flux at Station 8 at the outlet of the watershed (from 30 g/hr to 23 g/hr) when considering the entire TtNUS period of record. When normalizing the results by contributing area, the relatively large normalized contribution at Station 2 is greatly reduced by the more aggressive scenarios. In summary the model supports the conclusions based on the actual surface water data in that the “normalized” plots emphasize that the optimum location for remediation is upstream of Stations 2 and 4, given the large amount of arsenic contributed by the upstream areas relative to the volume of water.

1.0 INTRODUCTION

This report describes the results from a computer model that simulates surface water, suspended sediment, and metals transport within the Aberjona River Watershed. This report was prepared by Tetra Tech NUS, Inc. for the United States Environmental Protection Agency (EPA) under Work Assignment No. 116-RICO-0107, Contract No. 68-W6-0045 as part of the Industri-plex Superfund Site Multiple Source Groundwater Response Plan (MSGRP) Operable Unit 2 and including Wells G&H Superfund Site Aberjona River Study Operable Unit 3 (Study Area) investigations, specifically to supplement Feasibility Study (MSGRP FS).

1.1 Background

As part of a prior research project funded through the Massachusetts Institute of Technology (MIT), a program of measurements was implemented at five monitoring stations within the Aberjona River Watershed during the 1991 to 1993 time frame. Results from this monitoring program were used to develop a model of flow, sediment, and metals transport (As, Fe, Cr, and Cu) for the river (Solo-Gabriele and Perkins 1997b and 1997c). This model, the MIT-Aberjona Watershed Model (MIT-AWM), described transport at 4 locations throughout the watershed during the 1991 to 1993 time frame (Solo-Gabriele 1995; Solo-Gabriele and Perkins 1997a) and was then ultimately expanded to simulate transport during 1900 to 1993 (Solo-Gabriele 1998).

To expedite the computer modeling needs of the MSGRP FS, TtNUS contracted with the developer of the MIT-AWM model for the purpose of modifying the original MIT-AWM code. The code was to be altered to fit the monitoring program implemented by TtNUS during the 2001 to 2002 time period. The updated version of the model (i.e. TtNUS-AWM model) was used to support evaluation of a series of remediation alternatives that were identified during a recent remedial investigation (RI) and feasibility study (FS) conducted by TtNUS (TtNUS 2005a,b). The RI identified the metalloid, arsenic, as a contaminant of concern from both an ecological and human health standpoint, in particular within sediments within the Aberjona River.

1.2 Objectives and Report Organization

The TtNUS-AWM model was developed to serve as a screening tool for evaluating various remediation scenarios listed within the MSGRP FS. The model is intended to provide order-of-magnitude estimates for metal concentrations and fluxes that would be expected if metal inputs were to change at specific locations within the watershed. The model results should not be considered absolute and should be used with other measures to assess the potential impacts of various remediation scenarios.

The purpose of this report is to document the modifications to the MIT-AWM code, to document the performance of the calibrated TtNUS-AWM model for existing conditions, and to describe the results of the TtNUS-AWM model with respect to various remediation scenarios. The modifications to the MIT-AWM code were made in order to: a) accommodate the geometry of the TtNUS monitoring network established during 2001 to 2002, b) improve model performance given the additional data, and c) add simulation capabilities for two additional metals (lead and mercury) in addition to the original four metals included within MIT-AWM (arsenic, iron, chromium, and copper). The resulting TtNUS-AWM code was then calibrated and used to simulate various remediation scenarios.

The modifications to the MIT-AWM code are based upon data collected from the TtNUS surface water monitoring network established for the 2001-2002 time period. This network and the corresponding data set are summarized in Section 2.0. Section 3.0 describes the conceptual model for the TtNUS-AWM, which is consistent with the conceptual model for the MIT-AWM. The quantitative formulation of the model with an emphasis on changes from the MIT-AWM code are described in Section 4.0. Section 5.0 summarizes the calibration process, describes the performance of the model after calibration, and describes the results from a sensitivity analysis for the calibrated model. Results of the calibrated model with respect to the origin of water, sediments and metals are described in Section 6.0. The simulation of the various remediation scenarios is described in Section 7.0. A summary and conclusions are presented in Section 8.0. Appendices to this report are provided in the attached CD.

2.0 SUMMARY OF MONITORING DATA USED FOR MODEL INPUT AND CALIBRATION

Since the model relied heavily on monitoring data for both input and calibration a brief description of the monitoring program (Section 2.1), and results of hydrometerologic measurements (Section 2.2) and water quality data (Section 2.3) are provided in below. . More details about the monitoring program and data collected as part of the current study are provided in a comprehensive data report prepared by TtNUS entitled *Draft Evaluation of Flow, Suspended Sediment, and Heavy Metals in the Aberjona River*, dated January 2005, hereinafter referred to as TtNUS 2005 (TtNUS, 2005a)

2.1 Brief Description of Monitoring Program

The monitoring data for this study included results from a set of surface water monitoring stations constructed and maintained by TtNUS during an 18-month period beginning May 15, 2001 and ending October 29, 2002. The TtNUS data was supplemented with hydrometerological information from pre-existing monitoring stations including weather stations located in Reading and a USGS flow monitoring station. Eight of the 11 TtNUS stations were located within the model domain. At these eight stations semi-continuous data were collected for water flow. Furthermore, samples for suspended sediment and metals concentrations (dissolved and total) were collected through a monitoring program designed to capture trends during baseflow and storm flow conditions.

The most significant pre-existing weather stations located within or near the Aberjona Watershed included the Reading – NCDC Weather Station which has monitored daily precipitation since 1957, and the Reading – 100 Acre Pumping Station which has monitored daily precipitation since the late 1800s. Flow has been monitored since 1939 at the USGS station located near the outlet of the Aberjona River (Figure 2-1). Data from all of these stations was used for statistical analysis and for comparison with data collected from the TtNUS monitoring network.

Of the eight TtNUS stations located within the model domain, five were located along the main artery of the Aberjona River (Stations 3 and Stations 5 through 8) (Figure 2-1 and 2-2; Table 2-1). Station 3 was located immediately upstream of the confluence with outflows from the Halls Brook Holding Area (HBHA). Station 5 was located downstream of the Wells G and H wetland. Station 6 was located downstream of the Cranberry Bog Conservation Area. Station 7 was located at Swanton Street immediately downstream of the Atlantic Gelatin withdrawal wells. Station 8 was located immediately adjacent to the USGS monitoring station, which is near the outlet of the Aberjona River. The remaining 3 stations were located within the drainage basin of Halls Brook, HBHA, and HBHA wetlands. Station 1 was located at the confluence of Halls Brook and the HBHA. Station 2 was located immediately downstream of the HBHA and Station 4 was located at Mishawum Road immediately downstream of the HBHA wetland. Overall, the water within the watershed flows as follows: Stations 1 to 2 to 4. Water from Station 4 is then mixed with water from Station 3. The combined flows from Stations 3 and 4 flow towards 5 then to 6 and then to 7. Water from a large tributary to the Aberjona River, the Horn Pond Creek tributary, then combines with flows from Station 7. The combined flows from Horn Pond Creek and Station 7 then flow towards Station 8 which is located immediately next to the USGS flow monitoring station.

More details about the configuration of each station and processing of the data collected is provided in Section 2 of TtNUS 2005.

2.2 Brief Description of Monitoring Hydrometerologic Data Relevant to Model

The model requires two basic primary inputs: hourly temperature and hourly rainfall. The model directly utilized temperature data from the Reading – NCDC Weather Station which was needed to identify rainfall versus snow conditions and also used for the snowmelt routine. The amount of snow that fell during the TtNUS period of record was relatively small (0.65 inches out of 56.45 inches total precipitation) and thus, snowfall and snowmelt was not a significant factor in the amount or timing of flow within the river.

Hourly rainfall data were available at each of the TtNUS monitoring stations plus the Reading-NCDC station. Gaps in the data were filled with rainfall values from the next closest station. A total of 20 storm events with rainfall accumulation greater than 1-inch were observed during the TtNUS period of record. Of these events, 17 were greater than 1-inch but less than 2 inches; two events were greater than 2.0 inches but less than 3.0 inches; and one event was greater than 3.0 inches, with the largest event occurring in August 2001 at 3.08 inches. The frequency of storm events during the TtNUS period of record was consistent with historical records and overall the TtNUS period of record was consistent with average rainfall conditions.

The primary hydrologic output from the model is flow and for calibration purposes comparisons were made between modeled and measured flow values. Measured flow was obtained from semi-continuous depth measurements at each of the TtNUS monitoring stations and at the USGS station. Depth measurements were related to flow using a rating curve method. In general, the rating curves were very flat at low values indicating that at low water levels, small changes in water levels did not result in large changes in flow. At larger water depths, large increases in flow were observed with relatively small changes in water depth. More details about the processing of the TtNUS data to obtain water flows is provided in Section 2 of TtNUS 2005.

Comparison between the flows measured at TtNUS Station 8 and the USGS Station indicated that flows measured during the TtNUS monitoring period were representative of average conditions with the exception of the timing of the peak spring flows which occurred two months later than usual (in May versus March). (See TtNUS 2005 for more details of this analysis). Furthermore, evaluation of the data for TtNUS Stations 1 through 8 indicates that in general flow increases in the downstream direction. The primary exception to this trend was between Stations 2 and 4, where decreases were observed during months characterized by relatively high flows (Table 2-2).

2.3 Brief Description of Water Quality Data Relevant to Model

Water quality data used to calibrate the model included results of sample analysis for total suspended solids (TSS) and metals. The metals data used for model calibration purposes included the results for both filtered and unfiltered samples which represented the operationally defined dissolved phase and total metals concentrations, respectively. The difference between the two values represented the inferred particulate metals concentration. Metals concentrations and fluxes simulated by the model included arsenic, iron, chromium, copper, lead, and mercury. Samples were collected from each of the TtNUS stations during 16 baseflow events and six storm events. Of the storm events evaluated five were between 0.97 and 1.48 inches in accumulation. One, the May 12, 2002 storm, was characterized by 2.8 inches. Composite samples were collected during storm events at Stations 1, 2, 3, 5, 6, and 7. Grab samples were collected hourly during storm events at Stations 4 and 8.

TSS concentrations during baseflow conditions were consistently near 5 mg/L for all stations with the exception of Station 4, which was characterized by an average of 23 mg/L (ranged from 4 to 110 mg/L). The elevated TSS concentrations at Station 4 were observed during the fall and early winter months. These elevated levels may be due to possible turnover of a small pond located immediately upstream of this station. Early on during the modeling effort, attempts were made to correlate the elevated TSS concentrations at Station 4 with other hydrometerologic data such as air temperature, water temperature, and time of year. However, no consistent results were observed and so a model could not be developed to simulate the variability observed in the river at this point.

During storm events, TSS concentrations were higher for all stations located along the Aberjona River with the exception of Station 4. Stations exhibiting relatively high TSS concentrations during storm events included Station 1 (22 mg/L on average) and Station 8 (46 mg/L on average). As a result of the combined effects of increased concentrations and flows at these two stations, TSS fluxes also increased notably at these stations during storm conditions. TSS transport in the river is of significance since spikes in TSS were associated with spikes in metals transport.

Due to the spikes in TSS, total arsenic concentrations were greatest at each station during storm flow conditions, with the exception of Stations 3, 4, and 5. The increase in total arsenic was due to an increase in suspended sediment transport during storm events, which resulted in an overall increase in particulate arsenic concentrations. Although total arsenic concentrations decreased, on average, during storm event for Stations 3, 4, and 5 (as compared to baseflow), the total arsenic concentration observed at these stations was still the highest among all stations during storm event conditions. For the other metals (iron, chromium, copper, lead and mercury), the highest concentrations were observed at Station 4 during baseflow conditions. During storm flow conditions the highest concentrations for these same metals were typically observed at Stations 1 and 8. The elevated concentrations at Stations 1 and 8 were likely due to the elevated TSS concentrations observed at these station during storm events.

During baseflow conditions, metal fluxes typically increased from Station 1 to Station 2 to Station 4. The sum of the metal flux through Station 4 and 3, both of which flow towards Station 5, was typically greater than the flux observed at Station 5, suggesting that metals were depositing in areas immediately upstream of Station 5. When the fluxes were normalized by the corresponding drainage areas (g/(hr*mi^2), the highest normalized metal fluxes were consistently observed at Station 4 during baseflow conditions.

During storm flow conditions, a relatively large arsenic flux was observed at Station 2 on average. Iron flux was also high at Station 2 and increased systematically in the downstream direction from Station 5 to Station 8. The chromium, copper, and lead flux were generally elevated at Stations 1 and 8. When normalizing the storm flow metal fluxes on a drainage area basis (g/(hr*mi^2), the largest storm flow arsenic and iron flux corresponded to Station 2. The largest normalized fluxes for chromium, copper, and lead during storm events corresponded to Stations 1 and 8. Stations 1 and 8 also corresponded to the largest normalized TSS fluxes during storm events.

A summary of the concentrations and fluxes observed at each station are provided in Tables 2-3 and 2-4. More details about the TSS data are provided in Section 3.4 of TtNUS 2005. More details about the metals data are provided in Section of 4 of TtNUS 2005.

3.0 CONCEPTUAL MODEL

The geometry of the Aberjona watershed is represented in the model through a set of modules and channels (Section 3.1). Flow from each module is separated into components which include a quick storm response, a slow storm response, and long term baseflow (Section 3.2). Dissolved metals transport is modeled by assigning each flow component a dissolved metal concentration (Section 3.3). Suspended sediment inputs are associated with each flow component, plus the model permits for the deposition and erosion of suspended sediments within channels (Section 3.4). Particulate metals are modeled by assigning each suspended sediment source a particulate metals concentration (Section 3.5). Channels route the flow, suspended sediments, and metals from one gauging station to another. Deposition and erosion of suspended sediments and particulate metals is checked at the end of each channel. The total flow, suspended sediment, and metal concentrations in the river are the sum of the contributions coming from all of the upstream sources. More details of the conceptual model are provided in the sections below.

3.1 Watershed Geometry

The geometry of the watershed is conceptually represented through a series of modules which are inter-connected using channel components. Modules correspond to the area directly contributing flow to a particular TtNUS gauging station. These modules are defined through sub-basin delineations (Section 3.1.1). Channels route flow from each module from one gauging station to another (Section 3.1.2). The model also accounts for the removal of river water due to: a) losses observed between Stations 2 and 4, and b) groundwater pumping at the Atlantic Gelatin site (Section 3.1.3). All of these components are combined together to represent the overall watershed geometry (Section 3.1.4).

3.1.1 Sub-basin Delineation

The areas of the watershed contributing to each gauging station were delineated in order to define the modules for the model. Modules were determined by summing primary and secondary sub-basins within the Aberjona Watershed. Primary sub-basins were those that have been defined by the U.S. Geological Survey and are given numbers (e.g. Sub-basin 1, 2, etc…). Separation of the primary sub-basins into secondary basins was required to accommodate the geometry of the TtNUS monitoring network. Secondary basins are designated by the number of the primary basin followed by a letter (e.g. 1a, 1b, 1d, 1d, and 1e). Details concerning the separation of the watershed into sub-basins is provided in TtNUS 2005. A summary of the sub-basin delineation along with accompanying figures are provided in Table 3-1 and in Figures 3-1 through 3-3.

3.1.1.1 Module Delineation

A module is defined as the area contributing directly to a particular gauging station. Water that falls within the boundaries of Module 1 contributes flow directly to Station 1, the water that falls within the boundaries of Module 2 contributes flow directly to Station 2, and so on Primary and secondary sub-basins were thus summed to define a particular module (Table 3-1, Figures 3-2 and 3-3). Module 1 is the sum of Sub-basins 1C, 2, and 3. The area corresponding to Sub-basin 1B is the area corresponding to Module 2. Similarly the area corresponding to Sub-basin 1A is the area corresponding to Module 3 and Sub-basin 1D corresponds to Module 4. Module 5 is the sum of Sub-basins 1E and 5. Module 6 is the sum of Sub-basins 4 and 7. Module 7 is the sum of Sub-basins 6, 9, and 11. Module 8 is the sum of Sub-basins 12, 13B, and 15. The Woburn West Module corresponds to the area on the southwestern part of the watershed that is drained by Horn Pond Creek. This module corresponds to the sum of Sub-basins 8, 10, 13A, and 14.

3.1.2 Channel Components

Channels are used to route flow, suspended sediments, and metals from one monitoring station to another. Channels are defined by their length which corresponds to the length of the river between each corresponding gauging station. Channel A represents the length of the river between Stations 1 and 2. Channel B represents the length of the river between Stations 2 and 4. Channel C represents the length of the river between Stations 4 and 5 and so on (Table 3-2). The lengths of the river between corresponding stations were obtained directly from the USGS topographic map using AutoCad.

3.1.3 Water Withdrawals

The model is capable of simulating water withdrawals. There are two algorithms used: one which simulates withdrawals as a function of water depth and another which assumes a constant withdrawal rate.

3.1.3.1 Withdrawals as a Function of Water Depth

Surface water monitoring data indicated that water is lost between Stations 2 and 4. This loss was found to be a function of water depth, with higher water depths associated with larger losses of flow. The observed loss was likely associated with the control structure located at Station 4 which restricts the flow of water out of the HBHA wetland located between Stations 2 and 4. This control structure consists of a 5-foot diameter opening within a concrete wall. Presumably during large events, this structure causes water to flood within the upstream wetland, resulting in the discharge of surface water to the groundwater system at this location. Given the observed loss of surface water, the TtNUS-AWM model was updated to account for a water withdrawal between Stations 2 and 4. This withdrawal is a function of water depth at Station 4. More details of the formulation used to simulate this withdrawal is provided in Section 4.1.3.

3.1.3.2 Constant Withdrawal Rate

Groundwater is pumped from within the boundaries of the watershed. Such withdrawals would be anticipated to impact the surface water system, in particular if the groundwater wells are located near a river. Groundwater is generally pumped at a constant rate and so losses of surface water due to such pumping would be considered roughly constant in time. If the river and the groundwater at the withdrawal point are hydraulically well connected, it is conceivable that the amount of surface water withdrawn from the river is equivalent to the groundwater pumping rate. In the absence of additional data, the amount of water withdrawn from the river in areas impacted by groundwater pumping is considered to be equal to the pumping rate. In other words all of the water pumped by the Atlantic Gelatin wells is assumed to come from the river.

Major groundwater withdrawals from within the Aberjona Watershed include the Woburn Water Supply, the Burlington Water Supply, and the Atlantic Gelatin Withdrawal. All of these withdrawals represent net losses of water from the watershed, since the water from all of these wells is ultimately discharged to the MWRA sanitary sewer system. The water supply wells for the City of Woburn are located in the proximity of Horn Pond (refer to green squares on Figure 3-1). According to the Woburn Water Department, the average withdrawal from the wells at Horn Pond is 3.7 million gallons per day (mgd). The permitted withdrawal rate is 4.2 mgd. The Town of Burlington water supply has one of its water supply wells (Pump Station 8) located within the Aberjona River Watershed. The location of this well is at Wyman Street at the Burlington/Woburn town line. According to the Burlington Water Department, this well was deactivated during the early 1990s. Kraft Foods (Atlantic Gelatin) uses water from its wells for process wash water which is ultimately discharged to the MWRA sewer system. The Environmental Manager of Kraft Foods during October 2002 provided the information concerning the quantities of water withdrawn from the Atlantic Gelatin wells. According to the Environmental Manager, Kraft Foods has operated a total of seven wells (refer to green triangles on Figure 3-1). Of these wells only four (Wells 1, 2, 5, and 7) were active during the TtNUS monitoring period. Wells 1, 2, and 5 are located in Winchester adjacent to the Aberjona River. Well 4 is located near the main plant. Well 7 is located in Woburn near Whittemore Pond. The total permitted withdrawal rate for the active wells is 1 mgd or 1.55 cubic feet per second (cfs). Kraft Foods typically withdraws approximately 800,000 gpd from the Winchester wells and the balance (200,000 gallons per day [gpd]) is withdrawn from Well 7 at Whittemore Pond.

The groundwater withdrawal rates between the MIT and TtNUS monitoring periods are compared in Table 3-3. The TtNUS-AWM was adjusted to account for the decrease in groundwater withdrawals between the MIT and TtNUS monitoring periods. The withdrawal rates at Atlantic Gelatin for TtNUS-AWM was set to the 2001 to 2002 withdrawal rate of 1.55 cfs (= 1mgd). The remaining well clusters (City of Woburn and Town of Burlington) are located within the Woburn West sub-basin. In order to accommodate the reduction in groundwater withdrawals from the Woburn West module (0.9 mgd (4.5+0.1-3.7) = 1.4 cfs), the flow contribution from the Woburn West module was increased by 1.4 cfs due to the presumption that a decrease in groundwater withdrawals from within the sub-basin would result in a corresponding increase in flow.

3.1.4 Overall Representation of Watershed Geometry

The conceptual representation of the model consists of a series of modules inter-connected with channel components. As illustrated in Figure 3-4, TtNUS Station 1 receives the direct contribution from Module 1. Monitoring Station 2 receives the direct contribution from Module 2 plus routed flows from Channel A. Monitoring Station 3 receives the direct contribution from Module 3. Monitoring Station 4 receives the direct contributions from Module 4 plus the routed flows through Channel B. The routed flows through Channel B ultimately come from Modules 1 and 2. Furthermore, the model allows for the removal of water immediately upstream of Station 4. This capability was added to the model after the measured data indicated that water flows were lost between Stations 2 and 4. Monitoring Station 5 receives the direct contributions from Module 5 and the routed flows from Channel C. Similarly Station 6 receives the direct contributions from Module 6 and the routed flow from Channel D. Station 7 receives the direct contributions from Module 7 plus the routed flows from Channel E minus the water withdrawals associated with the Atlantic Gelatin area. Station 8 receives the direct contributions from Module 8 and the Woburn West Module plus the contributions from Channel F.

3.2 Conceptual Model for Water Sources

Water originates from the model from each module. Data has shown (Solo-Gabriele and Perkins, 1997a,b,c) that flow from the Aberjona River can be simulated as the sum of three components: a quick storm response, a slow storm response, and longterm baseflow (Figure 3-5). This response is observed in both the MIT period of record and in the TtNUS period of record (Compare upper and lower panels in Figure 3-5). “Quick storm flow” corresponds to the first peak of the streamflow hydrograph and is characterized by a rapid increase and subsequent rapid decrease in flow. These waters are presumably associated with processes such as (1) storm sewer flow; (2) direct precipitation into the channel; and (3) direct runoff close to the channel. “Slow storm flow” is associated with the slower rate of decline or with a second peak in streamflow after the first “quick” peak. These waters probably travel through the ground before entering the channel, and may include (1) interflow; and (2) ground-water sources associated with the raising of the water table due to storm water infiltration. Additionally for downstream gauging stations, the slow component may also incorporate flows from upstream source areas (a combination of quick and storm flows) whose response was attenuated by the routing effects of the river channel or engineered storm water detention structures. The longterm baseflow component responds to changes in precipitation and climate over seasonal time scales. Given these observations the following equation was used to model flow, Q_i, from each module at each time increment, i.

$$Q_j = flowq_j + flows_j + ltbf_j \qquad \text{eqn. 3.1}$$

Where $flowq_j$ = quick storm response from Module j
$flows_j$ = slow storm response from Module j
$ltbf_j$ = longterm baseflow from Module j

For the Woburn West Module, streamflow was not characterized by distinct quick, slow, and longterm baseflow components. Furthermore, during storm events, the magnitude of the streamflow at the outlet of Wedge Pond (inflow point to the Aberjona River) was much smaller than flow along the Aberjona River. The reason for this difference is primarily due to the storage effects of reservoirs Horn Pond and Wedge Pond within the Woburn West Module (Solo-Gabriele and Perkins, 1997b). Given the small flow during storm events, only one component of flow, "flowt", was considered for the Woburn West Module or:

$$Q_{ww} = flowt \qquad \text{eqn. 3.2}$$

Where the subscript "ww" corresponds to the Woburn West Module

Upon entering the channels, the streamflow inputs from a given module were subject to routing effects. For example, to model the flow at Station 2, the streamflow from Module 1 is routed through Channel A. The routed flow from Module 1 is then added to the streamflow input from Module 2; the sum of which is the modeled flow at Station 2.

3.3 Conceptual Model for Dissolved Metals

Earlier studies have shown that dissolved metals transport from each module on the Aberjona River can be sub-divided into several components (Solo-Gabriele and Perkins 1997c), where:

$$F_t = [M_d]_{net}Q = F_{quick} + F_{slow} + F_{ltbf} \qquad \text{eqn. 3.3}$$

$$= \overbrace{[M_d]_{quick}flow_q} + \overbrace{[M_d]_{slow}flow_s} + \overbrace{[M_d]_{ltbf}flow_{ltbf}}$$

Where F_t = total dissolved flux

$[M_d]_{net}$ = net dissolved metal concentration of water coming from a particular module

Q = total streamflow from a particular module

F_{quick} = dissolved flux associated with quick streamflow

F_{slow} = dissolved flux associated with slow streamflow

F_{ltbf} = dissolved flux associated with longterm baseflow

$[M_d]_i$ = dissolved metal concentration associated with streamflow component i

$flow_i$ = flow component i where q represents quick, s represents slow and ltbf represents longterm baseflow

By sub-dividing the total metal flux into components as given above, the observed changes in the dissolved metal concentration as observed from the water sampling data (TtNUS 2005a) can be explained by changes in the relative contribution of each of the dissolved metal components. For example, a dilution effect associated with storm flows can be explained by setting quick storm water and slow storm water at lower metals concentrations than longterm baseflow (i.e. $[M_d]_{quick} < [M_d]_{ltbf}$, $[M_d]_{slow} < [M_d]_{ltbf}$). Assume for instance that prior to and immediately after a storm event, longterm baseflow is the dominant component of water in the river (i.e. ltbf >> flowq, ltbf >> flows). Then during these conditions, the river water concentration would approach the dissolved metal concentration of the longterm baseflow component, or:

$$\begin{aligned}[M_d]_{net} &= \frac{[M_d]_{quick}flowq + [M_d]_{slow}flows + [M_d]_{ltbf}ltbf}{flowq + flows + ltbf} \qquad \text{eqn. 3.4}\\ &= \frac{\approx 0 + \approx 0 + [M_d]_{ltbf}ltbf}{\approx 0 + \approx 0 + ltbf}\\ &\approx [M_d]_{ltbf}\end{aligned}$$

During a large storm event, on the other hand, the longterm baseflow component of flow is generally much smaller than the quick and slow components of streamflow (i.e. ltbf << flowq, ltbf << flows). Assuming that the dissolved metal concentration are not orders-of-magnitude different from one another, then:

$$[M_d]_{net} = \frac{[M_d]_{quick}\,\text{flowq} + [M_d]_{slow}\,\text{flows} + [M_d]_{ltbf}\,\text{ltbf}}{\text{flowq} + \text{flows} + \text{ltbf}} \approx \frac{[M_d]_{quick}\,\text{flowq} + [M_d]_{slow}\,\text{flows}}{\text{flowq} + \text{flows}} \qquad \text{eqn. 3.5}$$

Since $[M_d]_{quick}$ and $[M_d]_{slow}$ were assumed to be lower than $[M_d]_{ltbf}$ then the dissolved metal concentration of the river would be lower during storm conditions than during low flows.

For simplification purposes, the dissolved metals concentrations of each of the components ($[M_d]_{quick}$, $[M_d]_{slow}$, $[M_d]_{ltbf}$) from each of the modules will be assumed constant in time; however, the time-constant-values can still be different from one another. In other words $[M_d]_{quick}$ for Module 1 can be different than $[M_d]_{quick}$ for Module 2. Furthermore, $[M_d]_{quick}$ for Module 1 can be different than $[M_d]_{slow}$ for Module 1. Thus it is re-emphasized that although the individual components are assumed constant in time, the net dissolved metal concentration coming from a particular module can vary in time due to changes in the relative contribution of each of the flow components (as presented in the example above).

For the Woburn West Module, there is only one dissolved metal component since only one streamflow component is considered, or:

$$F_t = [M_d]\text{flowt} \qquad \text{eqn. 3.6}$$

Once the dissolved metal inputs from each module enter the main channels, the dissolved metal fluxes are then routed and combined in a sequence that is identical to the sequence used for streamflow. At the Atlantic Gelatin site and at the water removal site upstream of Station 4, dissolved metals are assumed to be removed from the river along with the streamflow withdrawal.

3.4 Conceptual Model for Suspended Sediment Sources

Previous data had shown that along the Aberjona River different streamflow components entering the river have different sediment input characteristics (Solo-Gabriele and Perkins 1997b) (Figure 3-6), with quick waters contributing a large spike of sediments while slow storm waters and longterm baseflow contribute a low and relatively constant amount of suspended sediment. Similar patterns in suspended sediment concentrations were observed between the MIT and TtNUS monitoring periods. However, the magnitude of the peaks was much higher during the TtNUS period of record as compared to the MIT period of record (Compare upper and lower panels in Figure 3-6 and 3-7). Although differences in the magnitude of the peaks are noted between each data set, the peaks were consistently observed in the river when flow in the river was dominated by “quick” storm waters. Once slow storm flow started to influence the system, the concentrations decreased significantly back to baseline levels near 5 mg/L, as observed during both time periods. Given this observation, the conceptual model for was assumed to apply to both time periods; however, the calibration parameters that control the amount of sediment transported by the quick system will be varied to account for greater quantities of suspended sediments transported during the TtNUS monitoring period. Thus sediment inputs for each module were modeled in a similar fashion as for the MIT-AWM by separating sediment contributions into: 1) quick suspended sediments, "$smqs_{input}$", 2) slow suspended sediments, "$smss_{input}$", and 3) longterm baseflow suspended sediments, "$smbf_{input}$" (Figure 3.7).

A build-up/wash-off mechanism dominates the quick sediment source which contributes sediment to the river when either quick flow or rainfall is active. Slow and longterm baseflow sediments are characterized by low and relatively constant suspended sediment concentrations. Conceptually, these sediments are considered to be associated with groundwater inflows which have *a potential for forming particles* upon entering the river. Prior data also indicated that during some conditions, channel deposition and erosion may affect the amount of sediment transported from a given module. For example, during extremely low flows in the earlier data set, suspended sediment concentrations were observed to decrease linearly with streamflow (See inset within upper panel of Figure 3-7). The interpretation of this trend was that during these extremely low flow conditions, the transport capacity of the river had been reached and the excess sediment was being deposited within the channel. However, the more recent data set does not show evidence of suspended sediment deposition during extremely low flow conditions (see lower panel of Figure 3-7). As a result, this phenomenon was removed from the TtNUS-AWM. During extremely low flows, suspended sediments in the TtNUS-AWM do not deposit and thus the lowest suspended sediment concentration that can be observed in the river during extremely low flows is 5 mg/L, which corresponds to the concentrations associated with the slow flow component and longterm baseflows. Removal of “low flow” deposition greatly enhanced the performance of the TtNUS-AWM model with respect to simulating suspended sediment concentrations during low flow conditions. Within the TtNUS-AWM model, deposition can occur but only when the transport capacity is exceeded and this typically occurs only during the rising limb of the hydrograph when the amount of sediment entering the river exceeds the river’s capacity to transport it, thus emphasizing that sediment transport within the river is predominantly supply limited. The predominant supply, from the quick system, is active only during storm events thus resulting in bursts of sediment transport during storm conditions. After storm events, suspended sediment concentrations quickly fall to the 5 mg/L range, and in the case of the TtNUS-AWM, remain at 5 milligrams per liter (mg/L) until the next storm event when another burst of suspended sediments are transported. For the MIT-AWM, the suspended sediment concentrations were allowed to drop below 5 mg/L during extremely low flow conditions.

Even though the conditions by which sediment is deposited in the TtNUS-AWM model is different than that for the MIT-AWM model, both still account for deposition when the transport capacity is exceeded during storm events and thus both simulate the erosion of the deposited sediments. In order to simulate deposition and erosion, the sediment transport model for Modules 1 through 8 includes relationships by which sediment erosion, "$smch_{eros}$", deposition, "$smch_{depos}$", and transportable channel sediment, "$smch_{tr}$" *within each module* can be quantified (Figure 3-8). For the model, if the sum of the sediment inputs, smtot, ($smqs_{imput}$ + $smss_{imput}$ + $smbf_{imput}$ + $smch_{eros}$) exceeds the transport capacity, then the excess is deposited within the module’s channel. The amount deposited from each input is weighted on the mass contribution of that input. The difference between the input and the excess removed is the amount transported from each module. If the sum of the sediment input does not exceed the transported capacity, then the amount transported from the module is equal to the input (i.e. $smqs_{tr}$=$smqs_{input}$, $smss_{tr}$=$smss_{input}$, $smbf_{tr}$=$smbf_{input}$, $smch_{tr}$=$smch_{eros}$). The source of channel sediment (within each module) is assumed to only come from quick, slow, or longterm baseflow sediments which were deposited in the module channel during earlier times.

Sediment transport from the Woburn West Module differs from transport along the Aberjona River. For this module, sediment transport is characterized by two distinct types of sediments: organic and inorganic sediments (Solo-Gabriele and Perkins 1997b). For the organic phase, the longer the hydraulic residence time and the higher the water temperature, the larger the organic suspended sediment concentration. In capturing this effect, the Wedge Pond reservoir is modeled as a continuous-flow stirred-tank reactor for the growth of organic particles.

The inorganic phase was correlated with Wedge Pond hydraulic residence time: the longer the residence time the lower the inorganic suspended sediment concentration. The interpretation of this trend is that increased residence times within the reservoir permit more efficient settling of inorganic particulates. Therefore, the sediment transport model for the Woburn West Module, consists of two parts. One part is a continuous-flow stirred tank-reactor model which computes the organic suspended sediment concentration. The other part, estimates the inorganic concentration by relating it to hydraulic residence times.

Once the sediment contributions from each module are determined, the contributions are then routed and combined in a sequence which is dictated by watershed geometry (See Figure 3-4). The sequence was very similar to the sequence used for streamflow. The main differences are that: 1) at the end of each main channel unit (Channels A through F) a sediment deposition and erosion check is also included, and 2) at the water removal sites (upstream of Station 4 and at the Atlantic Gelatin site), sediments are *not* removed along with the streamflow.

A sediment deposition and erosion check is needed at the end of each main channel unit (Channels A through F) because the routing scheme redistributes the time history of the water and sediment fluxes. In other words, because of the redistribution of flow relative to sediment fluxes, there is a possibility that on the downstream end of each main channel unit the sediment transport capacity may be exceeded. Furthermore, if the capacity is not exceeded, there is a possibility of eroding channel sediments that were deposited during earlier times. The only source of sediments in the main channels is from routed sediments that were deposited when the transport capacity was exceeded.

At the water withdrawal sites, suspended sediments associated with the withdrawal are assumed to remain within the channel. Once the water is removed (without the sediment), then channel deposition and erosion are simulated. The relationships used are similar to those used for Modules 1 through 8 and for each main channel unit.

3.5 Conceptual Model for Particulate Metals

Particulate metal transport is modeled in a very similar fashion as dissolved metal transport in that particulate metals transported *from each module on the Aberjona River* can be subdivided into components, where:

$$F_t = [M_p]_{net} \frac{dsmtot_{tr}}{dt} = F_{quick} + F_{slow} + F_{ltbf} + F_{ch} \qquad \text{eqn. 3.7}$$

$$= [M_p]_{quick} \frac{dsmqs_{tr}}{dt} + [M_p]_{slow} \frac{dsmss_{tr}}{dt} + [M_p]_{ltbf} \frac{dsmbf_{tr}}{dt}$$

$$+ \{frq[M_p]_{quick} + frs[M_p]_{slow} + (1 - frq - frs)[M_p]_{ltbf}\} \frac{dsmch_{tr}}{dt}$$

where: F_t = total particulate metal flux (mass/time)

$[M_p]_{net}$ = net particulate metal concentration of suspended sediments coming from an Aberjona module (mass metal/mass ss)

$smtot_{tr}$ = total sediment mass transported from an Aberjona module = $smqs_{tr} + smss_{tr} + smbf_{tr} + smch_{tr}$

t = time

F_{quick} = particulate metal flux associated with quick streamflow

F_{slow} = particulate metal flux associated with slow streamflow

F_{ltbf} = particulate metal flux associated with longterm baseflow

F_{ch} = particulate metal flux associated with channel sediments

$[M_p]_i$ = particulate metal concentration associated with suspended sediment component i, (mass metal/mass ss)

frq = fraction of channel sediment from quick suspended sediments

frs = fraction of channel sediment from slow suspended sediments

By sub-dividing the total metal flux into components as give above, the observed changes in the river particulate metal concentrations, can be explained by changes in the relative contributions of each of the particulate metal components. Arguments similar to those present in Section 3.3 for the dissolved phase can be used to explain changes in "$[M_p]_{net}$" for the particulate phase. As for the dissolved phase, the particulate metal concentrations of each of the components ($[M_p]_{quick}$, $[M_p]_{slow}$, $[M_p]_{ltbf}$) from each of the sub basins will be assumed constant in time. However, the time-constant values can still be different from one another and can be different between modules.

For the Woburn West module, only one component of the particulate metal flux is considered:

$$F_t = [M_p] \frac{dsmtot}{dt} \qquad \text{eqn. 3.8}$$

where: smtot = sum of the organic and inorganic suspended sediments (mass)

Once the particulate metal inputs from each module enter the main channels, the particulate metal fluxes are then routed and combined in a sequence that is identical to the sequence used for suspended sediments. At the water withdrawal sites, particulate metals are assumed to deposit and erode in association with the suspended sediments.

4.0 FORMULATION OF THE MODEL

The purpose of the updated model was to simulate metal fluxes at each TtNUS monitoring station during the period when these stations were in operation (May 2001 to October 2002). The model developed for this study was a modification of a watershed-specific model developed at MIT during the 1991 to 1993 time frame (Solo-Gabriele and Perkins 1997a; Solo-Gabriele 1995). Inputs to the model include hourly precipitation, air temperature, and a series of input parameters used to simulate flow, suspended sediment transport, and metals transport in both the dissolved and particulate phases. The model is semi-distributed where inputs of water, sediments and metals are distributed throughout a set of modules which represent different areas of the watershed. These inputs are then routed in time through channel components within each module and through channels between each module. The model is semi-physically based with processes used to simulate flow, suspended sediment and metal transport possessing a physical meaning. However, the model does not use algorithms derived directly from theory in all cases. Some calibration parameters used by the model do have a direct physical interpretation, whereas others may represent a combination of several physically-based parameters lumped into one parameter. The model is thus considered to be a semi-distributed lumped-parameter model.

This Section provides summaries for the formulations used for basic model units (Section 4.1), with a particular emphasis on modifications since the MIT version of the model (Section 4.2). Please refer to Solo-Gabriele 1995 and Solo-Gabriele and Perkins 1997a for more in-depth descriptions of the original MIT version of the model including specifics of the algorithms. Many of the algorithms used in the updated TtNUS version of the model were obtained directly from the MIT version. A major modification to the TtNUS version of the model is in the order of computations which accommodate the new TtNUS monitoring network. Since there are more stations in the TtNUS monitoring network, there are many additional input files (Section 4.3) and output files (Section 4.4) needed to run the model.

4.1 <u>Basic Model Units</u>

The following sub-sections provide a brief description of the basic model units used in the TtNUS model. Please refer to Solo-Gabriele 1995 and Solo-Gabriele and Perkins 1997a for specific details concerning the mathematical formulations used within each of the basic model units. A brief description of the “basic model units” are included for Modules 1 through 8 (Section 4.1.1), the Woburn West Module (Section 4.1.2), the water withdrawals (Section 4.1.3), and main channels which separate modules (Section 4.1.4). A description of the computation sequence for each of the basic model units is provided in Section 4.1.5.

4.1.1 Outline for Modules 1 through 8

The inputs for the portion of the model used to simulate flow, sediment, and metals transport for Modules 1 through 8 include hourly precipitation and hourly ambient air temperature (Figure 4-1). If the temperature is greater than 32 degrees Fahrenheit (^{o}F), then the precipitation occurs as rain; if not, precipitation occurs as snow. From the hourly time sequence of rainfall, the effective rainfall (that portion of the rainfall that contributes directly to streamflow) is then calculated for the quick and slow systems. Effective rainfall computation for the quick system involves the separation of the hourly sequence of rainfall into individual storms using storm separation criteria specific to the quick system. For each storm, the total rainfall is then reduced to an effective rainfall by applying a quick-system runoff coefficient. The slow effective rainfall is computed in a similar fashion as that quick system except that slow-system parameters are used. The result is the computation of two different effective rainfalls: a quick-system effective rainfall and a slow-system effective rainfall.

A unit hydrograph technique is then used to route the effective rainfall to streamflow. Quick flow is computed using the quick effective rainfall and a quick unit hydrograph while slow flow is computed using the slow effective rainfall and a slow unit hydrograph.

Snow will accumulate as long as the temperature remains at or below 32 ^{o}F. Once the temperature rises above 32 ^{o}F, criteria are invoked by which the snowmelt process is initiated. Once the snow begins to melt, a degree-hour method is used to quantify the amount of snowmelt. Effective snowmelt is computed in a similar fashion as for the effective rainfall described above, except that melt-system parameters are used. A melt-flow unit hydrograph is then used to route the effective snowmelt. A fraction of the melt flow is then applied to the quick system while the remaining fraction is applied to the slow system.

Parameters which are used to estimate the longterm baseflow are also included as part of the input. These parameters include: 1) maximum, average, and minimum bi-monthly longterm baseflows as obtained from the USGS flow monitoring record located near the outlet of the Aberjona River, and 2) maximum, average, and minimum monthly precipitation as obtained from the Reading – NCDC weather station. To estimate the longterm baseflow at the USGS station for a model simulation step, the antecedent precipitation for the model period is compared to the historical longterm-baseflow records. The maximum longterm baseflow is then computed for a given module. For a module, the maximum longterm baseflow component is based upon: 1) the simulation-step longterm-baseflow value determine at the USGS station, 2) a multiplicative factor to estimate the maximum, 3) mass balance considerations, and 4) the areas of each of the individual modules. The longterm baseflow computed in this manner is then adjusted by assuming a linear increase in time during storm conditions and an exponential decrease in time after a storm event.

The total flow from a module is computed by summing the adjusted quick, adjusted slow, and longterm baseflows. Once each flow component has been determined, the dissolved-metal model is invoked, and assigns dissolved-metal concentration to each component.

After computation of the flow components, suspended sediments fluxes are then determined. Suspended sediments transport is separated into fluxes associated with quick, slow, longterm baseflow, and channel suspended sediments. Quick suspended sediments are modeled by assuming that there is an area physically separated from the river where sediments can accumulate. When either quick flow or rainfall is active, sediments can be flushed from this area to provide a supply of sediments to the river. Slow and longterm-baseflow sediments are modeled with low and constant suspended sediment concentrations. Channel sediments are a mixture of quick, slow, or longterm-baseflow sediment which have been deposited during prior time steps. Deposition and erosion of the channel sediments is based on a balance between sediment input and river transport capacities.

Once each component of suspended sediment has been determined, the particulate-metal flux is then modeled by assigning to each module and to each sediment component, a particulate-metal concentration (per mass of suspended sediment basis).

4.1.2 Outline for Woburn West Module

Inputs into the Woburn West Module (Figure 4-2) include: 1) streamflow, 2) water temperature, and 3) organic suspended sediment in the inflow. For this module, streamflow is assumed to consist of one component: the total streamflow. The input of the hourly streamflow consists of an interpolation of monthly streamflows as observed at the gauging station located at the outlet of Wedge Pond during the MIT period of the record (originally called gage 1 during the MIT monitoring period). The reason for this simplification is that during storm events: 1) consistently distinct components of flow were not apparent, and 2) the contribution of the Woburn West Module to streamflow along the Aberjona River was relatively small (Solo-Gabriele 1995 and Solo-Gabriele and Perkins 1997a). In order to accommodate changes in groundwater withdrawals between the MIT and TtNUS period of record, the contribution of water from the Woburn West module was increased by 1.4 cfs within the TtNUS-AWM due to a decrease in groundwater withdrawal rates during the TtNUS monitoring period (Refer to Section 3.1.3 for justification of the 1.4 cfs value).

Previous data collected during the MIT monitoring period also indicate that suspended sediments from the Woburn West module can be separated into two distinct types: organic and inorganic sediments. Observations showed that organic suspended sediments were strongly correlated with water temperature and with visual observations of high algal growth in the Wedge Pond reservoir. In capturing this effect, the Wedge Pond reservoir was modeled as a continuous-flow stirred-tank reactor for the growth of organic particulates. The organic suspended sediment concentration in the inflow to reservoir was assumed to be a constant in time. Within the reservoir, the concentration of organic suspended sediments was a function of the growth rate of organic particles and the hydraulic residence time of the water. The growth rate was assumed to be a function of water temperature. The hydraulic residence time was a function of streamflow and reservoir volume.

Previous data also indicated that the inorganic suspended sediments were correlated with the hydraulic residence time of the Wedge Pond reservoir. The longer the residence time the lower the inorganic suspended sediment concentration. The interpretation of this trend was that the reservoir essentially acts as a settling basin for inorganic particles. For this module, the inorganic concentration in the outflow was assumed to be inversely proportional to the residence time of the water.

For the dissolved phase, a dissolved-metal concentration was assigned to the total flow. Similarly, for the particulate phase, a constant particulate-metal concentration was assigned to the sum of the organic and inorganic suspended sediment fluxes. These concentrations were representative of the overall average dissolved and particulate concentration observed at the outlet of Wedge Pond during the MIT monitoring period. The need for a more elaborate model for metals was not warranted since the concentration of metals from this module were observed to be generally very low in comparison to the concentrations observed along the Aberjona River.

4.1.3 Outline for Water Withdrawals

Two different algorithms were used to simulate water withdrawals: one that was a function of water depth and another which was constant in time. The water withdrawal incorporated immediately upstream of Station 4 was a function of depth. The water withdrawal at the Atlantic Gelatin site was assumed constant with time.

Two different relationships were used to simulate water losses upstream of Station 4. As long as water levels were less than a set maximum value, maxl, then the water withdrawal upstream of Station 4, $loss_i$, was computed using the following expression:

$$loss_i = LL2 * (level_i - datum)^2 \qquad \text{eqn. 4.1}$$

where:
$loss_i$ = Amount of water lost at time step i, cfs
LL2 = Proportionality factor
datum = Reference depth, in feet above the invert of the circular outlet structure at Station 4
$level_i$ = Water level at time step i, ft. Since the model simulates flow, $level_i$ was back-calculated from the rating curve established for Station 4 (For more details concerning the rating curve, See Section 2.4 and Figure 2-6 in TtNUS 2005).

If the water level was higher than “maxl” then the loss of water was set equal to the value corresponding to a water level equal to “maxl” (Figure 4-3). The flow at Station 4 was then adjusted for the water loss.

Equation 4.1 is based upon Darcy's Law (Das 1985) which states that the velocity of water through a porous media is proportional to the hydraulic gradient, i, or:

$$v = k\ i \qquad \text{eqn. 4.2}$$

where: v = velocity of water flow, ft/s
k = proportionality factor, equivalent to the hydraulic conductivity, ft/s
i = hydraulic gradient, ft/ft

Assuming that the groundwater reference point outside of the Halls Brook Holding Area (HBHA) Wetland is given by "datum" (Figure 4-4) then the hydraulic gradient is defined by:

$$i = \frac{level_i - datum}{L} \qquad \text{eqn. 4.3}$$

where: L = the horizontal distance, in feet, between the outer edge of the surface water system and the point at which groundwater is measured. Since both $level_i$ and datum are referenced to the invert of the circular outlet structure at Station 4, the difference in the two numbers is the difference in water elevation between the surface water at Station 4 and groundwater. The loss of water would be in the direction perpendicular to the main axis of the HBHA wetland and so the cross-sectional area of flow, A, would be equal to the difference in water levels and the length of river over which the water is lost upstream of Station 4.

$$A = (level_i\text{-}datum) * L2 \qquad \text{eqn. 4.4}$$

Where: A = cross-sectional area of flow for the water lost, ft^2
L2 = Length of the river over which the water is lost, ft

Since the product of water velocity and cross-sectional area of flow is equal to the flow rate, then the flow rate of the water lost, $loss_i$, is given by the following expression.

$$loss_i = k * L2 * \frac{(level_i - datum)^2}{L} \qquad \text{eqn. 4.5}$$

Assuming that the values of "k", "L2", and "L" are constant in time, then these three values can be lumped into 1 value referred to as "LL2", as given in equation 4.1 above, for calibration purposes. One of the limitations of equation 4.1 is the assumption that the groundwater reference elevation is constant. In actuality this elevation would vary, in particular during storm events. During storm events, the groundwater reference point would rise along with a rise in the surface water elevation. In an effort to address this limitation, a maximum loss rate was established at a water level equivalent to “maxl”. “maxl” is also a calibration parameter along with the value of “datum”.

At Station 4, all the suspended sediments associated with the withdrawal are assumed to remain within the HBHA wetland. If the transport capacity of the river is exceeded, then the suspended sediments will deposit and accumulate; if not, previously deposited sediments can then be eroded from the HBHA wetland. Dissolved metals are assumed to be removed along with $loss_i$, whereas the particulate metals are assumed to remain within the HBHA wetland. Particulate metals that are deposited within the wetland have the potential to be eroded or resuspended when flow conditions increase.

The withdrawal at the Atlantic Gelatin area is modeled using conservation of mass (Figure 4-5). The groundwater removed from the Atlantic Gelatin site is assumed to be directly removed from the river, given the close proximity of the wells to surface water bodies within the watershed. As for the withdrawal at Station 4, all the suspended sediments associated with the Atlantic Gelatin withdrawal are assumed to remain within the channel. If the transport capacity of the river is exceeded, then the suspended sediments will deposit and accumulate; if not, previously deposited sediments can then be eroded from the channel bed. Dissolved metals are assumed to be removed along with the groundwater withdrawal, whereas the particulate metals are assumed to remain within the channel.

4.1.4 Outline for Main Channels (Channels A through F)

The purpose of the channels is to route the water, sediments, and metals from sub-basin to sub-basin (Figure 4-6). In this way, the timing effects of water and sediments coming from different areas of the watershed can be captured. The routing procedure used for streamflow is the Muskingum method. This procedure was modified such that the same method could be used to route sediment and metal fluxes. The input into the channel, are the combined flow, suspended sediment, and metal fluxes at the upstream end of each channel. The Muskingum router functions to attenuate the peaks and translate the centroid of the input in time. In doing so, the router redistributes the time history of streamflow relative to suspended sediment fluxes.

Due to the redistribution of streamflow and suspended sediment, a sediment deposition and erosion check is included at the end of each channel. If the suspended sediment flux at the end of the channel exceeds the transport capacity, then the excess is deposited. If the flux is lower than the capacity, then suspended sediment can be eroded.

4.1.5 Computation Sequence for Basic Model Units

The program begins by setting variables (real versus integer), setting dimensions for variables, and specifying the number of hours to be modeled. The begin date and time is set and the hourly temperature data is read. The model sets the Atlantic Gelatin withdrawal rate and reads the baseflow parameters. The program is initialized by reading the rainfall data for the most upstream module (Module 1). The flow from the Woburn West Module is computed. Computations then commence in the subsequent order: Module 1, Channel A, Module 2, Channel B, Module 3, and Module 4. Flow at Station 4 is adjusted for the water loss and the contribution from Station 3 and the net contribution from Station 4 are added together and then routed through Channel C. From here the computation sequence proceeds as follows: Module 5, Channel D, Module 6, Channel E, Module 7, Atlantic Gelatin Withdrawal, Channel F, Woburn West Sub-basin (for suspended sediments and metals), and Module 8. Summary files are then written to provide the results at each station for measured and modeled flow, suspended sediment and metal concentrations/fluxes in dissolved and particulate phases.

4.1.5.1 Computation Sequence for Modules 1 through 8

For each module the sequence of computations is as follows. First, sub-basin parameter files are read including files used to compute flow (ui.m?), metals (metals.m?), and suspended sediment transport (ss?.par), where ? corresponds to the module number. Precipitation data for that particular sub-basin is then read. Depending upon the air temperature at the time, the precipitation is then identified as rainfall or snowfall. Rainfall is then separated into different events and the effective rainfall is computed: one effective rainfall is computed for the quick system and another effective rainfall is computed for the slow system. The program then commences to compute the first two flow components – quick flow and slow flow - using a unit hydrograph technique. Flows due to snow melt are also computed using a unit hydrograph technique except the input for this unit is snow melt water instead of effective rainfall. The snow melt computation permits for the accumulation of snow as long as the ambient temperature is less than or equal to 32°F. Once the temperature rises above 32°F, the accumulated snow is then permitted to melt using a degree-day method, which allows for increases in the rate of snow melt as the temperature rises. Snow continues to melt until either no more snow is available or until the temperature falls below 32°F. Any remaining accumulated snow is then taken into consideration during the subsequent melt event. Once the snow melt water is computed, it is then routed in time using a unit hydrograph technique. The snow melt flow is then added to the slow component (40 percent) or quick component (60 percent) of flow. Longterm baseflow is based upon antecedent rainfall and melt water (previous 19 days). Depending upon antecedent conditions, the model then interpolates the longterm baseflow between a set of acceptable ranges of longterm baseflow for a particular month (see Section 4.2.2). These acceptable ranges are part of the input to the model.

Suspended sediment fluxes (mass of sediment per unit time) are then simulated once the different flow components are computed (quick flow, slow flow, and longterm baseflow with meltflow incorporated into either the quick flow or slow flow components). The input of sediment to each module is as follows. First sediments associated with "quick flow" are computed. "Quick" suspended sediments are computed through a build-up and wash-off mechanism. Between storm events, "quick" sediments accumulate or build-up over time in a fashion similar to that described by Overton and Meadows,1976. These sediments are then washed-off during storm events. Wash-off is a function of both the magnitude of quick flow and rainfall. Suspended sediments associated with slow storm flow and longterm baseflow are assumed to consist of a constant but low suspended sediment concentration. Thus the flux of these sediments to the river is generally small and proportional to the corresponding flow. The suspended solids inputs due to each component of flow are then added together and the transport capacity of the river is checked. If the amount of sediments input to the river is greater than the transport capacity then the sediments are deposited within the channel of the corresponding module. If the transport capacity is not exceeded then all of the sediment input to the river is transported downstream plus any previously deposited sediment is available for erosion up to the transport capacity. The transport capacity is a function of river flow. One transport capacity relationship is used for the rising limb of the streamflow hydrograph and another is used for the falling limb.

Once suspended sediments are computed, the model proceeds to compute metals transport. The model simulates metal transport by assigning each flow component and each suspended sediment component a metals concentration. Thus a dissolved metals concentration is assigned to the quick flow component, the slow flow component, and the longterm baseflow component. A particulate metal concentration is assigned to sediments originating from the quick flow system, from the slow flow system, and longterm baseflow. The concentration of sediments that are eroded from the channel are a combination of quick, slow, and longterm baseflow sediments that were deposited earlier and so the concentration of "channel" sediments depends upon the relative proportion of sediments deposited earlier.

4.1.5.2 Computation Sequence for the Woburn West Sub-basin

Streamflow for the Woburn West Module is an input to the model and is read at the very beginning of the main program. Suspended sediment and metal computations are performed after Channel F computations within the main program. The suspended sediment computation begins by initializing various sediment transport and metal concentrations parameters. At each time step, the inorganic and inorganic suspended sediment concentrations, the dissolved-metal fluxes and the particulate metal fluxes are computed. The inorganic suspended sediment concentration is modeled as a function of hydraulic residence time within the Wedge Pond reservoir. The organic suspended sediment concentration is modeled as a function of water temperature.

4.1.5.3 Computation Sequence for Main Channels (Channels A through F)

The computation sequence for the main channels essentially involves routing flow, suspended sediment flux, dissolved metals fluxes, and particulate metals fluxes individually through a channel routing scheme based upon the Muskingham routing method (Solo-Gabriele 1995). Once routed through the channel the suspended sediment, dissolved metals, and particulate metals concentrations are re-computed. Sediment and particulate metals fluxes are adjusted at the end of the channel for possible deposition and erosion.

4.1.5.4 Computation Sequence for the Withdrawal at Station 4

At Station 4 water losses are a function of water depth. These losses are subtracted from the sum of the flows from Module 4 and routed flows through Channel B which include the contributions from Modules 1 and 2. The dissolved metals corresponding to the water loss are assumed to be removed from the Aberjona River. The suspended sediments and particulate metals are assumed to remain in the HBHA wetland and can be carried downstream as long as the transport capacity of the river is not exceeded. If the transport capacity is exceeded then the suspended sediments and particulate metals will accumulate within the HBHA wetland and can be eroded at a later time when flows increase.

4.1.5.5 Computation Sequence for the Atlantic Gelatin Area

Within the Atlantic Gelatin site the water withdrawn by the wells is subtracted from the sum of the flows from Module 7 and routed flows through Channel E. As for the withdrawal at Station 4, the dissolved metals corresponding to the Atlantic Gelatin withdrawal are assumed to be removed from the Aberjona River. The suspended sediments and particulate metals are assumed to remain in the channel and will be carried downstream as long as the transport capacity of the river is not exceeded. If the transport capacity is exceeded then the suspended sediments and particulate metals will accumulate within the Atlantic Gelatin area and can be eroded at a later time when flows increase.

4.1.5.6 Computation Sequence and Comparisons With Data Collected at Monitoring Stations

In order to compare modeled data to measured data, the contributions from all of the upstream modules are added together at the corresponding monitoring station (Refer to Figure 3-4). For example, only the output from Module 1 is compared to the data collected at Monitoring Station 1. The data from Monitoring Station 2 is compared to the output from Module 2 plus the routed constituents from Module 1. The data collected at Monitoring Station 3 is compared only to the output from Module 3. Monitoring data collected at Station 4 is compared with the sum of the inputs from Module 4 minus the loss, and the routed constituents from Modules 1 and 2, where the constituents from Module 1 are routed through channels A and B and the constituents from Module 2 are routed through channel B. The fluxes from Stations 3 and 4 are then added and routed through Channel C. Similarly for Monitoring Stations 5 and 6, the data collected at each station is compared to the sum of the output from the module immediately upstream plus the routed constituents as observed at the end of the channel unit immediately upstream of the station. The monitoring data collected at Station 7 is the sum of the contributions from Module 7 plus channel E minus the removal due to the Atlantic Gelatin withdrawal. The data collected at monitoring Station 8 is compared to the sum of the contributions from the Woburn West Module, Module 8 and Channel F. Most of these comparisons are established through output files that are generated near the end of the main program.

4.2 Details Concerning Updates to the Model

The original MIT model and input files were converted from a UNIX based system to a PC based system. The PC compatible version of the model was compiled using Lahey Fortran 95 Pro v 5.7. The major update to the model, once recompiled in PC compatible Fortran, was its ability to evaluate data at the additional TtNUS monitoring stations. The original MIT model modeled utilized a total of 3 sub-basins (or modules) along the main branch of the Aberjona River plus the Woburn West Module. The updated TtNUS model simulates flow from 8 different modules plus the Woburn West Module. Furthermore, a water withdrawal was added to the area immediately upstream of Station 4 (as described earlier). Originally only one input file was utilized for rainfall for the entire watershed. The updated version permits for the input of different hourly rainfall values with a different file for each of the 8 modules. Similarly calibration parameters for suspended sediment simulations were fixed for all 3 modules of the original MIT model. In the updated TtNUS version of the model, the suspended sediment calibration parameters were permitted to vary between stations, between channels, and at the two withdrawal points (Atlantic Gelatin and upstream of Station 4). Furthermore, modeling capabilities for two additional metals, lead and mercury, were added to the model in addition to the original four metals of iron, arsenic, chromium, and copper. In order to facilitate the updates to the new TtNUS code, many of the repetitive computations and functions were moved from the main program of the MIT model into subroutines (see Section 4.2.1). Other modifications to the model include updating the “fixed” input parameters used for simulating longterm baseflow (Section 4.2.2) and setting the minimum suspended sediment transport capacity to 5 mg/L (Section 3.4).

4.2.1 Model Subroutines

The model consists of a main code and 36 subroutines. Nineteen of these subroutines were added to the TtNUS version of the model in an effort to consolidate repetitive algorithms. These subroutines include: concen, cum, dmconcw, met, metwr, pmconc, ssdcm, ssdcwr, sumdata, sum2, sum2w, sum3, sum3w, wr, writflow, wrmetc, wrmetf. Brief descriptions of these subroutines are provided in Table 4.1. Other major subroutines added to the updated code included two (wqstat and compo) which facilitated the evaluation of water quality data. “Wqstat” is designed to evaluate data obtained from grab samples and “compo” is designed to evaluate data obtained from composite samples.

4.2.2 Longterm Baseflow

The computation of longterm baseflow for a given sub-basin begins by first determining the longterm baseflow at the USGS Station, since a long record of streamflow is available for this station. To determine the longterm baseflow at the USGS station for a given time step, the sum of the precipitation over the prior 19 days is computed. The 19 days corresponds to the response time of the longterm baseflow system and was determined by evaluating the streamflow record at the USGS station (Solo-Gabriele 1995). The basic assumption is that the precipitation occurring over the 19 days immediately preceding the current time step will affect the longterm baseflow at that current time step. Once the 19-day antecedent precipitation has been determined, the value is compared with the historical precipitation and longterm-baseflow records. An interpolation scheme is then used to estimate the longterm baseflow at Station 8 for a given model time step. The interpolation scheme compares the 19-day antecedent precipitation with the historical records of antecedent precipitation and longterm baseflow. For example, if the 19-day antecedent precipitation is high as compared to the historical record, then the interpolation scheme provides a high value of longterm baseflow for that current time step as compared to the historical record. Similarly if the 19-day antecedent precipitation is low then the long term baseflow for the current time step is interpolated as a low value as compared to the historical record.

The longterm baseflow for a given sub-basin is then computed using mass balance considerations and is based upon a weighted average of the contributing area from a particular module. The corresponding equation is as follows:

$$ltbf_{i,j} = [LTBF_{USGS,i} + agwith - bfww_i]\frac{A_j}{\sum_{j=1}^{n} A_j} \qquad \text{eqn. 4.6}$$

where $ltbf_{i,j}$ = longterm baseflow for module j at time step i

$LTBF_{USGS,i}$ = longterm baseflow at the USGS station at time step i

agwith = Atlantic Gelatin withdrawal, constant

$bfww_i$ = longterm baseflow for Woburn West Module at time step i

A_j = area of module j

n = total number of modules upstream of the USGS Station or TtNUS Station 8 not including the Woburn West Module

The Woburn West baseflow is assumed constant and equal to 1.53 cfs, which corresponds to the minimum flow from this sub-basin as measured during the 1991 to 1993 MIT period of record. The Atlantic Gelatin withdrawal is set to a constant of 1.55 cfs, which corresponds to the reported pumping rate at these wells during the TtNUS monitoring period. The withdrawal at Station 4 is not included in the equation 4.6 because this withdrawal is most predominant when water levels are high, during storm conditions. Withdrawals at Station 4 during baseflow conditions are thus negligible.

During a storm event the modeled value of the longterm baseflow for a given module can increase by 0.25 cfs during each time increment until a maximum is reached. The maximum value is set at 1.2 times the $ltbf_{i,j}$ as determined from equation 4.6. Upon reaching the maximum, the modeled value of the longterm baseflow will remain at the maximum until after the storm. The 0.25 cfs and 1.2 factors were determined by a calibration process (Solo-Gabriele 1995). The end of the storm corresponds to the time when the slow flow component is less than 0.05 cfs. At this time, the longterm baseflow component is permitted to decrease exponentially according to the following relationship:

$$ltbf_i = 10^{\log(ltbf_{i-1}) - R} \qquad \text{eqn. 4.7}$$

where i = time step i

R = time constant for the longterm baseflow system = 0.0022/hr

Note that the inverse value of R is equal to 19 days which corresponds to the response time of the longterm-baseflow system.

The major change in the longterm-baseflow computation was in the historical precipitation data and longterm baseflow values that were used to compute the $LTBF_{USGS,i}$ value in equation 4.6. The interpolation parameters include: 1) bimonthly maximum, average, and minimum longterm baseflows as obtained from the USGS station and 2) the maximum, average, and minimum monthly precipitation as obtained from the Reading – NCDC Weather station record. The corresponding file is called “bf_new.ave” as opposed to “bf.ave” which was used in the original MIT code. The primary difference between “bf_new.ave” and “bf.ave” was the period of record evaluated in developing each input file. “bf_new.ave” uses precipitation and flow data for the 1957 to 2002 period of record where as “bf.ave” uses data for the 1957 to 1993 period of record.

The same procedure used to determine “bf.ave” was used to determine the corresponding values in “bf_new.ave”. The procedure involved updating a set of computer programs (usgsbf_update.f, usgsbf2_update.f, plotbf_update.m) which provide bi-monthly values of baseflow and monthly precipitation. These programs are included in the attached CD. (See the “/Baseflow_Update” directory). The program “usgsbf_update.f” identified days during which streamflow was likely dominated by longterm baseflow. Criteria used to identify these days was based upon the slope of the recession curve and upon antecedent precipitation. The primary assumption was that days characterized by a relatively flat receding limb and by small antecedent rainfalls are considered to be days which could be dominated by longterm baseflow. The specific criteria used were the same as those used during MIT model development. These criteria included:

a) $0 <= slope < k$, where slope = $\log_{10}(flow_{i-1} – \log_{10}flow_i)$. $Flow_i$ is the daily average streamflow for a given day, i, and $flow_{i-1}$ is the daily average streamflow for the previous day. The recession constant, k, was set to 0.054/day. The inverse of this constant corresponds to 19 days which was the time constant determined for longterm baseflow.

b) $Precip_{i-1} < 0.04$ inches, where $precip_{i-1}$ is the precipitation depth at the Reading station for the previous day.

The days and flow values identified were then super-imposed on the streamflow hydrographs (plotbf_update.m) and points were eliminated which were not considered baseflow. Points eliminated included days occurring along the peak of the hydrographs and plateau points not associated with baseflow. After the elimination of erroneous data points, the average, maximum, and minimum bi-monthly longterm baseflows were then computed along with the average monthly precipitation to provide the updated “bf_new.ave” file. The data points used to determine the values provided in “bf_new.ave” are illustrated in Figure 4-7.

4.2.3 Summary

In summary major updates to the model included:

- Conversion of code and corresponding input files from UNIX based system to PC based system. Compilation of the PC version is based upon Lahey Fortran 95 Pro v 5.7.

- Re-organization of the code to accommodate geometry of the TtNUS monitoring network. This required the addition of sub-routines which streamlined repetitive algorithms.

- Allowed different rainfall inputs for each separate module instead of one rainfall data set for the entire watershed.

- Allowed suspended sediment calibration parameters to vary between modules and between channels and setting the minimum suspended sediment transport capacity for the river to 5 mg/L.

- Added a module to simulate the water withdrawal upstream of Station 4, as a function of water depth.

- Updated the input file utilized to model longterm baseflow. This updated file is based upon the 1957 to 2002 USGS flow record.

- Addition of subroutines that facilitate the evaluation of data obtained from grab and composite samples.

- Added simulation capabilities for two additional metals, lead and mercury, in addition to arsenic, iron, chromium and copper.

4.3 Model Input

The computer model accepts two types of input: "fixed" input and "calibration" input. Some input files contain only "fixed" input, some contain only "calibration" input, and some contain both "fixed" and "calibration" input (Table 4-2). All input files are included in the attached CD. (See the "/Input_Files" directory). "Fixed" input is fixed and does not change from run to run. Calibration inputs are parameters used by the model which are varied until the best fit is obtained between the measured and modeled data. Examples of fixed input files include "temp.01" which provides hourly air temperature data for the watershed for November through April. The model only uses temperature values during these months for hours when the temperature is at or above 32^0F. Hourly precipitation data is provided by the rain?.txt files, where the "?" corresponds to the module number. The flow?.01 files correspond to the measured flow data at each of the monitoring stations for module "?". The file flusgs.txt summarizes the measured flow at the USGS station. Flowww.txt is a dummy file with all values of –999 which tells the model that there is no measured flow from the Woburn West Module. Other examples of "fixed" input files include me?_BD.txt and me?comp_BD.txt which summarize the measured results from suspended sediment and metals analysis (dissolved and total metals). Me?_BD.txt summarizes the results for the grab samples whereas me?comp_BD.txt summarizes the results for the composite samples. In these files the concentrations that were measured at below detection limit values were set to ½ the detection limit. However, when calibrating the model for Cr, Cu, Pb, and Hg the ½ detection limit values were not used and rather samples that measured below detection limits were not included within the calibration process, thus biasing the calibration for Cr, Cu, Pb, and Hg slightly high. The file "bf_new.ave" is a fixed input file that is used when computing the longterm baseflow for each module.

The files referred to as ui.m? contain the input needed for the computation of flow from each module. This file contains "fixed" input such as the surface area of each module. This file also contains "calibration" input that include IAQ, IAS, IAM, KQ, KS, and KM. Furthermore, these files contain fixed input including TQ, TS, TM, and the ordinates of the unit hydrographs for the quick, slow, and snowmelt systems (Table 4-3). These parameters are used to compute quick storm flow, slow storm flow, and meltwater flow given the effective rainfall for the quick system, the effective rainfall for the slow system, and the effective snow melt. The effective rainfall is first computed by separating individual storm events using a “water response time” criterion (TQ, TS, TM for quick, slow, and snowmelt systems, respectively) which were considered fixed parameters for the TtNUS-AWM. The water response time criterion can be considered as the time needed to empty most of the system of water after rainfall has ceased. The underlying assumption in the use of a water response time is that once the system is empty an additional amount of water (i.e. the initial abstraction, IAQ, IAS, and IAM for the quick, slow, and snowmelt systems respectively) is needed before the system can start supplying water to the river. The initial abstraction is applied only when the water response time has elapsed. Once a storm event begins, the initial abstraction is assumed “lost” from the system. If the total storm depth is less than the initial abstraction, no water is converted to effective rainfall. If the storm depth is greater than the initial abstraction, then a fraction of the remaining rainfall (KQ, KS, or KM) is assumed to contribute to the effective rainfall. More details are provided by Solo-Gabriele, 1995. The calibration parameters of KQ, KS, and KM represent the fraction of remaining rainfall that contributes to effective rainfall for the quick, slow, and meltwater systems, respectively. The unit hydrographs utilized to compute quick, slow, and melt flows are the same as those calibrated for the original MIT model and are thus used for Modules 1 through 8. The unit hydrograph ordinates were therefore not calibrated as part of the TtNUS modeling effort.

In addition to the calibration parameters of IAQ, IAS, IAM, KQ, KS, KM, three additional calibration parameters were used to control the water withdrawal immediately upstream of Station 4. These calibration parameters included a) “maxl” which corresponds to the water depth at which the maximum withdrawal occurs, b) “LL2” a proportionality factor which relates the amount of water loss to the difference in water levels between the surface water and the groundwater at Station 4, and c) “datum” which is the reference point for the groundwater system. More details about these calibration parameters are provided in Section 4.1.3.

Calibration parameters for suspended sediment transport from a module (Table 4-3) are included in either ss?.par files or ss?p.par files, where the ? corresponds to either a module number or a channel. Furthermore, two additional files, ssag.par and ssr4.par are used to control suspended sediment transport in the vicinity of the Atlantic Gelatin groundwater withdrawal and at the point of water loss at Station 4, respectively. Ss?.par includes calibration parameters for describing sediment transport from a module. Several parameters are included specifically for the “quick” system (ss?.par files only). The source of “quick” suspended sediment is simulated through a build-up and wash-off mechanism. The build-up of sediments within a module is simulated through the following calibration parameters: “maxlq” which is the input deposition rate of sediment in units of grams per hour per square mile; “k” input loss rate coefficient per hour. Accumulation is the difference between input (maxlq times the surface area of the module) and the product of k times the amount of sediment accumulated. Thus the net accumulation of sediment is the difference between a constant term and a term that increases as the amount of sediment accumulates. This essentially results in rapid accumulation of sediment when there are few sediments available and a slower accumulation of sediment as the amount of sediment build-up. Sediments from the quick areas can be released through either rainfall or quick flow. Quick flow can access the entire area of sediments; rainfall can access a fraction of the quick area, frac. The user of the model can also adjust a threshold for rainfall associated erosion of sediment, thresr, such that no erosion occurs for values of rainfall less than or equal to thresr. The amount of sediments carried by rainfall and quick flows is a function of Cr and Cq, which are erosion factors due to rainfall and quick flows, respectively. The larger the values of Cr and Cq the greater the amount of sediment that is transported due to a given rainfall and quick flow rate, respectively.

The concentration of suspended sediments in the water column during times dominated by slow flows and longterm baseflows is defined by the value of bfpot. “f” is an initiation parameter which represents the fraction of channel sediment from the “slow” system at time, t, equal to zero. This parameter is of importance in defining the initial concentration of metals within those channel sediments since different concentrations are associated with the different sediment components. “f” however, only affects the metal concentration during the early time steps, since subsequent deposition and erosion of sediments as simulated by the model will significantly alter the composition of deposited sediments within various channel components. Erosion of sediments from channels is defined by the calibration parameter Cq. The larger Cq the more sediments eroded for a given flow rate. A value of Cq can be assigned to channels within each module and to channel components that connect each module.

Calibration of metals requires assigning each flow component (quick, slow, and longterm baseflow) a dissolved metals concentration and assigning each sediment component (quick, slow, and longterm baseflow sediments) a particulate metals concentration (Table 4-4). The units for dissolved metals were µg/L except for iron where the units were in mg/L. Particulate metals were assigned units of milligrams of metal per kilogram of sediment, except for iron which was assigned in units of parts per hundred or percent. Therefore, for each module there were 6 calibration values per metal ($[M_d]_{quick}$, $[M_d]_{slow}$, $[M_d]_{ltbf}$, $[M_p]_{quick}$, $[M_p]_{slow}$, $[M_p]_{ltbf}$). Given that there were 6 metals simulated by the model, a total of 36 metals calibration parameters were set per module. The primary exception corresponded to the Woburn West Module where only one metal concentration value was assigned to the dissolved phase and only one metal concentration was assigned to the particulate phase for a total of two calibration parameters per metal or 12 calibration parameters for all six metals simulated.

4.4 Model Output

Over 250 files are output by the model (See Table 4-5 for a complete list of the output files). These files provide output for each module, the Woburn West Module, each channel, and for the Atlantic Gelatin area and for the water removal at Station 4. In addition to these files, output files are generated which summarize particular sections of the model.

The output for each module (Module 1 through 8) includes: 1) a flow file (f.m? where ? corresponds to a module number) which includes data for quick, slow, longterm baseflow, and meltwater components, 2) a suspended sediment file (ss.m?) which includes data for suspended sediment associated with quick, slow, longterm baseflow, and channel components, 3) dissolved metals associated with each flow component (Fed.m?, Asd.m?, Crd.m?, Cud.m?, Cud.m?, Pbd.m?, Hgd.m?, where for example Fed.m? corresponds to the dissolved iron concentration from module ?), 4) particulate metals associated with each flow component (Fep.m?, Asp.m?, Crp.m?, Cup.m?, Cup.m?, Pbp.m?, Hgp.m?), 5) files containing modeled and measured metals concentrations for grab samples (mo?.txt), 5) files containing modeled and measured metals concentrations for composite samples (mo?comp.txt), and 6) files containing the storm averaged data (modeled and measured) for each composite sample (ma?comp.txt).

Output for the Woburn West Module includes the following files which provide modeled data at the outlet of this sub-basin: 1) a flow file (f.ww), 2) a suspended sediment file (ss.ww) which contains suspended sediment fluxes and concentrations, 3) dissolved metals files (Asd.ww, Fed.ww, Crd.ww, Cud,ww, Cud.ww, Pbd.ww, and Hgd.ww where the first two letters in the file name correspond to the metal simulated) which provide dissolved metals concentrations and fluxes, 4) particulate metals files (Fep.ww, Asp.ww, Crp.ww, Cup.ww, Pbp.ww, and Hgp.ww) which provide particulate metals concentrations and fluxes,

Output for each channel includes following files which provide modeled data at the end of each channel for Channels A through F: 1) a flow file (f?.c?) where ? corresponds to the channel letter, 2) a suspended sediment file (ss?.c?) which provides both fluxes and concentrations, 3) dissolved metals files (Asd?.c?, Fed?.c?, Crd?.c?, Cud?.c?, Pbd?.c?, Hgd?.c?) which provide dissolved metals concentrations and fluxes, 4) particulate metals files (Asp?.c?, Fep?.c?, Crp?.c?, Cup?.c?, Pbp?.c?, Hgp?.c?) which provide particulate metals concentrations and fluxes,

Output for the water loss at Station 4 and at the Atlantic Gelatin area includes the following files which provide modeled data immediately following the withdrawal points: 1) flow files (f.r4 and f.ag) which includes modeled flow after the Station 4 loss point and the Atlantic Gelatin withdrawal, respectively, 2) a suspended sediment files, (ssa.r4 and ssa.ag) which provides the suspended sediment masses and concentrations at each location, 3) dissolved metals files for the water loss at Station 4 (Asd.r4, Fed.r4, Crd.r4, Cud.r4, Pbd.r4, Hgd.r4) and for the withdrawal at the Atlantic Gelatin site (Asda.ag, Feda.ag, Crda.ag, Cuda.ag, Pbda.ag, Hgda.ag) which provides dissolved metals concentrations and fluxes, 4) particulate metals files for the water loss at Station 4 (Asp.r4, Fep.r4, Crp.r4, Cup.r4, Pbp.r4, Hgp.r4) and for the water withdrawal at the Atlantic Gelatin site (Aspa.ag, Fepa.ag, Crpa.ag, Cupa.ag, Pbpa.ag, Hgpa.ag) which provide particulate metals concentrations and fluxes.

In addition to the files above, special files are generated which compare data from different modules and which are used to check model performance. These files include: 1) “storms,” which summarizes the date and depth of each storm observed at each module, 2) “out.check” which provides a comparison between modeled and measured flow for each monitoring station, 3) “out.che” which is the same as “out.check” except text for the column headings has been removed for direct input into Matlab, 4) “mirror.txt” which lists the input parameters to check that the input was read correctly, 5) “balance” which provides mass balance information for flow, suspended sediments, and metals, 6) “wqbalance” which provides a listing of modeled versus measured metals concentrations for both grab and composite samples, 7) “ssconc2.conc” which provides a listing of modeled suspended sediment concentrations at each station, 8) “ssconc.conc” which is the same as “ssconc2.conc” but with the column headings removed, 9) “temp?f.flux” which provides a listing of the dissolved and particulate metals fluxes, where ? equals F, A, R, U, P, and H for iron, arsenic, chromium, copper, lead, and mercury, respectively, 10) “ssflux2.flux” which provides a listing of modeled suspended sediment fluxes at each station, 11) “ssflux.flux” same as “ssflux2.flux” except with the column headings removed, and 12) “temp?c.conc” which provides a listing of dissolved and particulate metals concentrations, where ? equals F, A, R, U, P, and H for iron, arsenic, chromium, copper, lead, and mercury, respectively.

4.5 Post-Processing of Model Output

Output files generated by the model were graphed using Matlab Version 6.5, Release 13 for the qualitative evaluation of the results. Fifty-five script files (Table 4-6) were written. These plot files can graph the output data generated for the entire TtNUS period of record except that only a maximum of 1 month of data can be plotted at any one given time. A “master” file was written to automate the generation of various sets of plots. These master files were designed to plot the results for each station for each year simulated in a semi-automated fashion.

There were eight files written to plot the measured and modeled flow and suspended sediment concentration data at Stations 1 through 8 with one file corresponding to each station (plot_flowss?.m where ? corresponds to the station number). For Station 8, the plot files also included a comparison with flow data measured at the USGS station. A “master” file was written to automate the generation of the plot_flowss?.m plots. The name of the file master was “john_plot_flowss.m”. An additional 36 script files were prepared to graph metals concentrations. Eight of these files (for Stations 1 through 8) were prepared for arsenic (plot_As?.m), eight were prepared for iron (plot_Fe?.m), and eight were prepared for chromium (plot_Cr?.m). For the remaining metals, plot files were prepared for Stations 1, 2, 4, and 8 (plot_Cu?.m, plot_Pb?.m, and plot_Hg?.m). The plots for these files are separated into two sub-plots: one for the dissolved metal concentrations and one for the total metal concentrations. These files include the modeled concentrations and the measured data. Measured grab sample data are depicted in these files by the “o” symbol and the results from the measured composite sample data are depicted by the “x” symbol. Concentrations values for samples that measured below the detection limit were set at ½ the detection limit value. A “master” file was written to automate the generation of the arsenic concentration plots. The name of the master file was “john_plot_As.m”.

Eight additional script files were written to provide a comparison between modeled and measured arsenic fluxes (plot_As?flux.m) where ? corresponds to the station number. Again, the plot area is separated into two sub-plots: one for dissolved arsenic flux and another for the total arsenic flux. The flux graphed on these figures corresponds to the product of the flow and the corresponding arsenic concentration. If the arsenic concentration data are below the detection limit, then the concentration is assumed at ½ the detection limit value for flux computation purposes. As in the previous set of plot files, the “o” symbol corresponds to flux values obtained using grab sample data for the concentration value and the “x” symbol corresponds to flux values obtained using composite sample data.

5.0 MODEL CALIBRATION AND PERFORMANCE

Calibration of the model followed either a two-tiered (flow and suspended sediments) or a one-tiered approach (metals). For the two-tiered approach an automated optimization computer program was written to obtain the best fit parameters. The data from the optimization program were then reviewed by the modelers and additional fine-tuning of the calibration was performed subjectively based upon the modelers' best judgment using various criteria (McCuen 1989). In the one-tiered approach used for metals, no computerized optimization program was used as the calibration was much simpler once the flow and suspended sediment parameters were set. For the streamflow model, the criteria used for calibration included: 1) mass balance considerations, 2) R^2 or goodness of fit values, and 3) visual comparison of time series plots. After calibration for flow the model's performance was further evaluated through histogram plots and computation of additional statistics. For suspended sediment and metals the criteria for calibration were: 1) mass balance considerations, and 2) visual comparison of time series plots. This section focuses on summarizing the calibration scheme and discussing the calibration parameters optimized for the model (Section 5.1) and documenting the performance of the model by presenting statistics and time series plots of modeled versus measured data (Section 5.2). Results from a sensitivity analysis are provided in Section 5.3. A review of the model by an independent consulting firm, Watermark, is provided in Appendix A.

5.1 Calibration

Calibration of the model was conducted for each of the following sub-models separately. These sub-models focus on the simulation of streamflow (Section 5.1.1), dissolved metals (Section 5.1.2), suspended sediments (Section 5.1.3), and particulate metals (Section 5.1.4). The automated optimization program developed for flow and suspended sediment parameters was based upon the univariate method (Rao 1996). The method involved changing only one calibration parameter at a time until the values of the calibration criteria were optimized. The optimization involved minimizing the difference between modeled and measured average values for flow and suspended sediment concentrations, and for flow maximizing the R^2 value. The method requires first identifying the direction of change for a particular calibration parameter.

This is first determined by changing the calibration parameter by a small increment. This increment is added to the calibration parameter and the model is run. The increment is also subtracted from the calibration parameter and the model is rerun. If both runs indicate that the calibration should go in a particular direction, then the calibration continues in that direction. If not, then the optimum value is found for that particular calibration parameter. Once the criteria were optimized for the first calibration parameter, then the same procedure was applied to the second calibration parameter and so forth. Once all calibration parameters were optimized in this fashion, the entire process was started over, with the first calibration parameter, until no further improvement was observed in the calibration criteria (i.e. objective function). “No further improvement” was defined as less than a 1 percent change in the criteria used for optimization. Usually only one iteration among the calibration parameters was necessary in order to identify an optimum set of calibration parameters.

In order to facilitate the explanation of calibration and measured parameters, the symbols included in circles ◯ in the following equations correspond to measured values and the symbols included in squares □ correspond to calibration values. The sum of the symbols on the right hand side of the equations corresponds to the modeled values.

5.1.1 Streamflow Model

The streamflow portion of the model was calibrated first since streamflow affects all of the water quality parameters. Calibration was performed on comparisons between measured and modeled streamflow. Modeled streamflow at station i, Q_i, was the sum of the quick flow ($flowq_i$), slow flow ($flows_i$), and longterm baseflow ($ltbf_i$) from the module immediately upstream plus any contributions from upstream modules which have been attenuated by channel components (equation 5.1).

$$Q_i = flowq_i + flows_i + ltbf_i + \{\text{upstream contributions}\} \quad \text{eqn. 5.1}$$

$\boxed{IAQ_i}$ $\boxed{KQ_i}$ $\boxed{IAS_i}$ $\boxed{KS_i}$

$\boxed{IAM_i}$ $\boxed{KM_i}$

Thus, calibration proceeded in the downstream direction from Station 1 through Station 8, noting that Station 3 does not contribute flows to Station 4. The parameters adjusted included the rainfall parameters used to compute the quick effective rainfall (IAQ_i and KQ_i), the slow effective rainfall (IAS_i and KS_i), and the effective snowmelt (IAM_i and KM_i), where the subscript “i” corresponds to the module number. The initial abstractions for each system in units of inches are provided by IAQ_i, IAS_i, and IAM_i. The fraction of the remaining rainfall or snowmelt that is converted to streamflow is computed from KQ_i, KS_i, and KM_i. Furthermore, for Station 4, the calibration parameters used to control the loss of water between Stations 2 and 4 were included in the optimization program. These parameters included “datum”, “LL2”, and “maxl”. These additional parameters are described in more detail in Section 4.1.3. All other parameters of the streamflow model including the ordinates of the unit hydrographs were the same as those used for the MIT version of the model.

The criteria used for automatic optimization of the flow model (first tier) included the square of the difference of the mean flows (measured-modeled)^2 plus the R^2 value. For consistency, only modeled data corresponding to times where measured data were available were used for the computation of the mean flows. Also, for reporting purposes, the difference between measured and modeled flows was expressed in percent units as follows:

$$mass\ balance\ \%\ error = \frac{measured\ mean\ flow - \mathrm{mod}eled\ mean\ flow}{measured\ mean\ flow} * 100\% \qquad \text{eqn. 5.2b}$$

The closer the percent error is to zero the better the model performance. Percent errors within plus or minus 20% were considered acceptable. This limit of percent error was chosen because it corresponded to the “match” of flow measurements between TtNUS Station 8 and the measurements taken by the U.S.G.S. at the same location (TtNUS 2005). The R^2 value used for computation purposes (Chasen 1978) is also known as the coefficient of efficiency or more specifically as the Nash-Sutcliff coefficient of efficiency (Legates and McCabe 1999). The R^2 value is defined in equation form as:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(measured_i - \mathrm{mod}eled_i)^2}{\sum_{i=1}^{N}(measured_i - mean\ measured)^2} \qquad \text{eqn. 5.1a}$$

Acceptable values for R^2 were those that were between 0.7 and 1 (Solo-Gabriele 1995). The higher the value is to one the better the fit. A value of one represents a perfect fit, whereas a value less than zero indicates that the model performed worse than simply using the average streamflow.

For the flow model optimization program, the optimization criteria (or objective function) was the square of the mean flow difference (measured-model)^2 plus the R^2. The results were sensitive to the weighting that was given to R^2 in the objective function. Depending upon the model run, the two criteria were weighted, usually by a factor of 25 percent for the square of the mean flow difference and 75 percent for the R^2. The reason that R^2 was more heavily weighted was because it was a more sensitive criteria. If the objective function used only R^2 then the program usually provided only one set of calibration parameters that gave the optimal value for R^2. If the mean flow difference was used, several different sets of parameters were possible depending upon the values at which the search was initiated. On some occasions a second run was performed using soley the mean flow difference or the R^2 to determine which parameters were the optimum for those criteria. These observations were taken into consideration when selecting the optimum calibration parameters.

The calibration parameters optimized for each module were IAQ, IAS, IAM, KQ, KS, and KM. In addition for Station 4, datum, LL2, and maxl were included in the optimization program. The final result of the optimization program was very sensitive to the order used for the calibration parameters (variables) in the optimization scheme. The optimum order was determined to be KS, IAS, KQ, IAQ, KM, and IAM and for runs corresponding to Module 4, the order was to remain the same but then maxl, LL2, and datum were added in that order. On occasions the order was changed to determine if better calibration parameters could be found.

The model calibration was fine-tuned with a second tier of calibration. The second tier of calibration relied on a subjective optimization method which included evaluation of time series plots in addition to the criteria listed above (difference between modeled and measured mean flow and R^2 values). Time series plots are extremely useful since they can be used to evaluate many different aspects of model performance. These aspects include: 1) the magnitude of peaks, 2) timing of peaks, the characteristics of the receding limbs, 4) characteristics of low flows, and 5) the overall patterns between modeled and measured flows. Pattern recognition is one aspect of time series plots which is not available through other criteria and is also the aspect which makes time series plots especially useful when calibrating a model. The main drawback associated with time series plots is their qualitative nature. When using time series plots to evaluate model performance, there is no quantitative measure by which models can be ranked with respect to another. Rather the user is required to make a subjective judgment.
Once the model was calibrated, performance was further evaluated through the use of

histograms and percentile values between measured and modeled flows. Histograms are plots of streamflow versus the number of occurrences. These plots enable the user to quickly pin-point the range of streamflows in which the model does not perform properly. For example, from a histogram plot, one can quickly determine whether too few peaks or whether too few low flows are modeled. These plots do not penalize for time shifts between modeled and measured flows. Percentile values evaluated correspond to the flow value at which a set percentage of the values were greater. Percentile values are provided in tabular form and represent an alternate to histogram plots for evaluating the "number of occurrences" of a particular range of flow rates. The percentile values evaluated for modeled and measured flows included the 5, 10, 25, 50, 75, 90, and 95 values.

The calibration parameters (Table 5-1 and 5-2) indicate that the initial abstraction for Module 4 for the quick system (direct runoff) is the largest among all of the modules suggesting that surface runoff (e.g. quick system) from this module, which includes the Halls Brook Holding Area, does not respond to rainfall for small storm events (<0.5 inches). The initial abstractions for the slow and melt flow systems varied from zero for Station 2, to 0.52 for IAS at Station 5 and 0.95 for IAM for Station 4. The fraction of rainfall or snowmelt that is converted to streamflow is the smallest for Module 4 for the quick system, again emphasizing that surface water flow from this module does not contribute significantly to the quick flow component during storm events. KQ values are relatively large for the stations farthest downstream (KQ = 0.2 for Station 7 and KQ = 0.35 for Station 8) which is consistent with the increase in urbanization within the Modules located further south. The values of KS varied from 0.1 to 0.6 with relatively large values for Modules 2, 5, and 8, suggesting that flow from these modules is characterized by a relatively large interflow component. The large value of KS for Station 5 coupled with the relatively large IAS, is consistent with the occurrence of a wetland (Wells G&H) immediately upstream since wetlands have a tendency to attenuate peak flows and promote a slower response. KM values are fairly consistent among all of the modules, between 0.7 and 1 and suggest that a majority of the snowmelt results in river flow. The total amount of snow during the TtNUS period of record, however, was relatively small (0.65 inches) representing about 1percent of the total precipitation and thus the model was not particularly sensitive to the snowmelt parameters.

The datum for the water loss between Stations 2 and 4 was calibrated at just above the invert of the outlet control structure (0.04 feet above). Once the water level reached a depth of 3.1 feet the loss was set to a constant rate corresponding to the loss that occurs at 3.1 feet (Table 5-2).

5.1.2 Dissolved Metals Model

The dissolved-metals parameters were calibrated after the streamflow model was calibrated. Dissolved-metal parameters included the assignment of dissolved-metal concentrations to each component of flow ($[M_d]_{quick,i}$, $[M_d]_{slow,i}$, $[M_d]_{ltbf,i}$) from each module, i, where $[M_d]_{quick,i}$ corresponds to the quick flow system, $[M_d]_{slow,i}$ corresponds to the slow flow system, and $[M_d]_{ltbf,i}$ corresponds to the longterm baseflow system. The measured values used for calibration included the dissolved metal concentration measured at TtNUS Station, i, ($[M_d]_{overall,i}$) as indicated by equation 5.2.

$$[M_d]_{overall,i} = \frac{\boxed{[M_d]_{quick,i}}\, flowq_i + \boxed{[M_d]_{slow,i}}\, flows_i + \boxed{[M_d]_{ltbf,i}}\, ltbf_i}{Q_i} \qquad \text{eqn. 5.2}$$

Results from the calibration (Table 5-3) indicate that the dissolved metals parameters for Module 2 were elevated for arsenic. Groundwater components from Module 3 and 8, in particular $[As_d]_{ltbf}$ were elevated in comparison to other modules. The quick dissolved arsenic component for Station 6 was also elevated. Iron concentrations for all components were relatively elevated for Modules 2 and 4. Dissolved chromium concentrations were relatively uniform with higher concentrations generally associated with the quick component. Copper and lead concentrations were more sporadic with a very high copper concentration calibrated for the quick component for Station 6 and relatively high dissolved lead concentrations for Module 4, for the quick component for Station 7, and for the longterm baseflow component for Module 8. Mercury levels were essentially set to zeros with the exception of Module 4.

5.1.3 Suspended Sediment Model

Suspended sediments originating from a particular module are the sum of the sediments that are transported from the quick system, from the slow system, and from the longterm baseflow system plus the sediments that are eroded from channels located within the module. These contributions are then added to all upstream contributions of sediments to obtain the suspended sediment concentration at a particular station, $[SS]_{overall,i}$. The suspended sediment fluxes from upstream areas are adjusted by channel components that link modules. These channel components redistribute flow and suspended sediments in time and recomputed sediment deposition and erosion at the end of each main channel component.

The calibration parameters used to simulate sediment inputs from the quick system include those parameters that are directly related to the rainfall effects on sediment transport, thresr, frac, and Cr, and those that correspond to the effects of quick flow, thresq, maxlq, k, and Cq . Erosion of sediment from channels within a sub-basin is controlled through Cs. Bfpot is used to simulate sediment transport from the slow and longterm baseflow systems. (See Section 6.3 for a description of these parameters). The overall suspended sediment flux from a particular module, i, is thus the sum of the fluxes from that module which include flux transported from the quick system, $smqs_{tr,i}$, the slow system, $smss_{tr,i}$, and the longterm baseflow system $smbf_{tr,i}$, plus the flux due to the erosion of previously deposited sediment during times when flows are high, $smch_{eros,i}$. The total flux from the module is then added to upstream sources of flux, with Module 3 not included in the sum of contributions to Station 4. Given that flux is the product of flow and concentration, the suspended sediment concentration at a particular station, i, ([SS]overall,i) is then computed by dividing the sum of the fluxes by the flow at station i, Q_i.

Quickflow Induced Erosion
$\boxed{thresq}$ $\boxed{maxlq}$ $\boxed{k}$ $\boxed{Cq}$

Rainfall Induced Erosion
$\boxed{thresr}$ $\boxed{frac}$ $\boxed{Cr}$

$\boxed{bfpot}$ $\boxed{Cs}$

$$[SS]_{overall,i} = \frac{smqs_{tr} + smss_{tr} + smbf_{tr} + smch_{eros} + \{upstream\_sources\}}{Q_i} \qquad \text{eqn 5.3}$$

The criteria used for automatic optimization of the suspended sediment model (first tier) included the square of the difference of the mean suspended sediments (measured-modeled). The square of the difference for both grab and composite samples was used for Stations 1, 2, 3, 5, 6, and 7. Only grab sample data was collected and thus utilized for the optimization routines for Stations 4 and 8. For consistency, only modeled data corresponding to times when measured data were available were used for the computation of the mean suspended sediment concentrations. The optimized calibration parameters were sensitive to the weighting included in the objective function (grab versus composites) and to the order in which the calibration parameters were optimized. For Stations 1, 2, 3, 5, 6, and 7, the calibration parameters were not sensitive to the grab sample suspended sediment concentrations as all the grab samples were collected during low flow conditions and measured suspended sediment concentrations were almost constant during these times. Optimization of the parameters was weighed more heavily upon the composite data for these stations. The optimum order for calibrating the parameters was as follows: Cs, Cq, Cr, frac, and maxlq. Attempts were made to keep the remaining suspended sediment calibration parameters (f, bfpot, thresq, k, and thresr) constant.

The sediment accumulation term, maxlq, varied from 200,000 for Modules 1, 2, 3, and 6, to a value of 100,000 for Module 8 and a value of 50,000 for modules 4, 5, and 7 (Table 5-4). Sartor and Boyd, 1972, provide accumulation rates for various land uses. For solids loads (maxlq/k) they listed values of 1200, 2800, and 290 lb/curb_mile for residential, industrial, and commercial land-uses, respectively. For urbanized lands within the Aberjona Watershed there are approximately 42 curb miles per square mile (Solo-Gabriele 1995). Applying various conversion factors, the modeled values of maxlq is computed as:

$$\frac{\max lq}{k} = \frac{50{,}000 \, {}^{g}\!/\!_{hr \bullet mi^2}}{0.01 \, {}^{}\!/\!_{hr}} \; to \; \frac{200{,}000 \, {}^{g}\!/\!_{hr \bullet mi^2}}{0.01 \, {}^{}\!/\!_{hr}}$$

$$= 5 \times 10^6 \quad \text{to} \quad 20 \times 10^6 \quad \text{g/mi}^2$$

$$= 262 \quad \text{to} \quad 1050 \quad \text{lb/curb\_mile}$$

The values above are very near the values listed by Sartor and Boyd for accumulation sediment accumulation rates. In Overton and Meadows, 1976, the rates of solids accumulation, maxlq, are listed as 590, 1400, and 180 lb/(curb_mile*day) for residential, industrial, and commercial land uses, respectively. The model value of maxlq was determined as:

$$\text{maxlq} = 50{,}000 \text{ g/(hr*mi}^2\text{)} \;\; \text{to } 200{,}000\text{/(hr*mi}^2\text{)}$$

$$= 13 \quad \text{to} \quad 250 \text{ lb/(curb\_mile*day)}$$

These values are somewhat on the low end of maxlq values measured by Overton and Meadows.

The values of thresq = 0 and thresr = 0 indicate that the critical velocities required to initiate motion are small compared to the values of “flowq” and “rain”, which are input values (rain) or values simulated by the model (flowq). Overall, calibration parameters that impact erosion from within a module (Cs, Cq, and Cr) are largest for Modules 1, 6, and 8 indicating that once sediment is deposited within these modules it has a tendency to be eroded quickly (Table 5-4). Converting the values of Cq (in units of $(1/hr)*(mi^2/cfs)^4$ to units consistent with that Cr results in values from 5200 to 69×10^6 $(1/hr)*(hr/in)^4$. These values of Cq are much larger than the values of Cr (from 1.3 to 3). Such results indicate that quick flow is a much more efficient eroder of sediment than rainfall. In areas where the value of frac = 0 (module 2, 4, 5, and 7), rainfall has no direct impact on sediment transport since the area impacted by rainfall is zero as indicated by the “frac” parameters. In other modules, 20 percent of the sediment accumulation area is assumed to be impacted by rainfall, thereby providing for direct rainfall impacts on sediment transport.

Bfpot, which is the potential concentration of suspended sediments associated with slow flow and longterm baseflow, is consistently at 5 mg/L for all modules. The bulk of the waters from both the slow and longterm-baseflow systems may be assumed to travel through the ground prior to discharge into the river. Since the same value of bfpot was satisfactory for each system, apparently the aquifer is capable of imparting a potential suspended sediment concentration on each of these waters. For the Aberjona River the potential concentration imparted by the aquifer was 1) constant regardless of the response time of a given system (i.e. bfpot of the slow system equals the bfpot for the longterm baseflow system) and 2) constant in time for a particular system.

The values of Cs (1×10^{-7} to 8×10^{-5} $(1/hr)*(mi^2/cfs)^4$) were sometimes larger and sometimes smaller than the corresponding values of Cq. Cs is the erosion coefficient for the channel whereas Cq is the erosion coefficient for quick areas. In areas where Cs is larger than Cq, the channel generally serves to mobilize the sediments eroded by the quick areas very efficiently resulting in minimal build up of sediments within the module channels. In areas where Cq is much larger than Cs, sediments tend to accumulate more within the module channels.

Channels that link modules have a similar set of sediment-transport calibration parameters (Table 5-5), which include the bfpot and Cs which is the parameter that controls erosion from the channels. The values for these parameters were relatively large for Channels D and F. The values for the remaining channels were zero or near zero. Such results suggest that sediments that deposit within Channels D and F are efficiently eroded downstream. Within Channels A, B, and E, which are characterized by Cs values of zero, sediments that deposit within the channel tend to remain within the channel. Deposition of sediments within the TtNUS-AWM version of the model is not as significant as simulated with the earlier MIT-AWM version, because deposition is not considered in the TtNUS-AWM version of the model during extremely low flows, due to lack of evidence of such a phenomena from the measured data.

Similarly at the water withdrawal points, the f and bfpot values were consistent with values used for the channel components and the modules. The value of Cs for the Atlantic Gelatin withdrawal site was the same as that observed for Channel D whereas the Cs value for the loss upstream of Station 4 was on the low end, similar to that observed for Channel C, again indicating that once sediments are deposited in this area they have a tendency to accumulate.

5.1.4 Particulate Metals Model

The particulate-metals parameters were calibrated after the suspended sediment model was calibrated. Particulate-metal parameters included the assignment of particulate-metal concentrations ($[M_p]_{quick,i}$, $[M_p]_{slow,i}$, $[M_p]_{ltbf,i}$) to each component of sediment flux from each module, i, where $[M_p]_{quick,i}$ corresponds to quick sediments, $[M_p]_{slow,I}$ corresponds to the slow sediments, and $[M_p]_{ltbf,I}$ corresponds to longterm baseflow sediments. Unfortunately a direct measure of $[M_p]_{overall,i}$ was not available since the concentration of metals *on the suspended solids* was not measured. As a result, $[M_p]_{overall,i}$ was calibrated indirectly through *total* metals concentrations measurements as shown in equations 5.4 through 5.6, since total metals are the sum of the dissolved plus the particulate metals. Thus the calibration of the particulate metals concentrations was indirect and was dependent upon an accurate estimate of the dissolved metals concentration, $[M_d]_{overall,i}$, and the suspended sediment concentration, $[SS]_{overall,i}$. As a consequence, care should be taken when interpreting the results of these calibration parameters, given that they were calibrated against an indirect measure of particulate metals concentrations. If the values of $[M_p]$ are of interest in and of themselves, they should be checked against direct measures of $[M_p]$.

eqn. 5.4

$$\underbrace{F_t}_{\text{Total Metal Flux}} = \underbrace{F_d}_{\text{Dissolved Metal Flux}} + \underbrace{F_P}_{\text{Particulate Metal Flux}}$$

$$\underbrace{[M_t]_{overall,i}Q_i}_{\text{Total Metal Flux}} = \underbrace{[M_d]_{overall,i}Q_i}_{\text{Dissolved Metal Flux}} + \underbrace{[M_p]_{overall,i}[SS]_{overall,i}Q_i}_{\text{Particulate Metal Flux}}$$

Dividing equation 5.4 by Q_i

$$[M_t]_{overall,i} = [M_d]_{overall,i} + [M_p]_{overall,i}[SS]_{overall,i} \qquad \text{eqn. 5.5}$$

Furthermore

$$[M_p]_{overall,i} = \frac{\boxed{[M_p]_{quick,i}}smqs_{tr,i} + \boxed{[M_p]_{slow,i}}smss_{tr,i} + \boxed{[M_p]_{ltbf,i}}smbf_{tr,i}}{Q_i} \qquad \text{eqn. 5.6}$$

$$+ \frac{\{frq\boxed{[M_p]_{quick,i}} + frs\boxed{[M_p]_{slow,i}} + (1 - frq - frs)\boxed{[M_p]_{ltbf}}\}smch_{tr,i}}{Q_i}$$

As observed from Table 5-6, the highest particulate arsenic concentrations were calibrated for Module 2. The calibrated particulate arsenic concentrations were also high for Modules 3 and 5. Particulate iron concentrations were relatively high for Modules 1 through 5. Particulate chromium concentrations were variable with very high values for Module 5 and for the longterm baseflow component for Module 8. Module 5 was also characterized by elevated concentrations of particulate copper and lead, specifically for the quick component. Particulate copper and lead were also high for the longterm baseflow component for Module 8. Particulate mercury was generally zero except for Module 4, 5, and the quick component of Module 6.

5.2 Performance

Model performance is documented for the streamflow model (Section 5.2.1), for the dissolved metals model (Section 5.2.2), for the suspended sediment model (Section 5.2.3), and for the particulate metals model (Section 5.2.4). Furthermore, given that metals flux was one of the primary parameters to be modeled, additional plots are provided towards the end of this section (Section 5.2.5) that provide comparisons between modeled and measured arsenic fluxes. It is important to mention that results from both grab and composite samples were utilized in establishing the optimum calibration parameters for the suspended sediment and metals portions of the model. Grab samples were collected for Stations 1, 2, 3, 5, 6, and 7 during baseflow conditions only. Only composite samples were collected for these same stations during storm events. Grab samples were collected during both baseflow and storm events at Stations 4 and 8. No composite samples were collected at these two stations. Thus the following grab sample statistics include baseflow and storm flow data for Stations 4 and 8 and only baseflow data for the remaining stations. Composite sample statistics are provided for Stations 1, 2, 3, 5, 6, and 7 during storm flow conditions.

Time series plots were evaluated for all of the data on a month by month basis. For the flow model this involved the evaluation of 18 time series plots per station for a total of 144 plots. Similarly, for the suspended sediment model there were a total of 144 plots to evaluate (18*8). For the dissolved metals model, there were 18 time series plots per metal per station for a total of 648 plots (18*8*3 + 18*4*3). Similarly there were a total of 648 plots to evaluate for the particulate metals model. Time series plots are provided for Stations 4 and 8 only in the main text, given that water quality samples at these stations were collected on an hourly basis, versus composite samples at the other stations.

The model keeps track of water flows and sediment/metals fluxes. Since much of the measured data was in units of concentration, the model computed concentration values for water quality parameters at each of the TtNUS monitoring stations for comparison with the measured data. Concentration was computed as the flux divided by the flow (equation 5.7). As a consequence, when flows were very low, there were large variations in the concentration value due to having a very small number (i.e. flow) in the denominator.

$$Concentration = \frac{Flux}{Flow} \qquad \text{eqn. 5.7}$$

Large fluctuations in concentration at very low flows, even though flux was relatively constant

During very low flows, the sediment and metal fluxes were also very low and were not affected by the variability in the computed concentration. This particular problem was especially apparent at Station 7 which is immediately downstream of the Atlantic Gelatin withdrawal. Flows at this station were extremely low on occasion due to the withdrawal and thus concentrations (not fluxes) computed by the model were subject to significant variability. As a result, data corresponding to modeled flows less than 0.3 cfs were not included in the statistics provided below for Station 7. This omission focuses the criteria towards times when significant fluxes were moving through the river.

5.2.1 Streamflow Model

The differences between modeled and measured flow were within 1 to 2 cfs on average (Table 5-7) and so mass balance for streamflow was maintained within reason for each TtNUS monitoring station. Typically, the percent differences were within 10 percent to 20 percent. The overall R^2 values were considered to be very good with most stations near 0.7 or higher, which is considered excellent for environmental data. Also included within the data are statistics for the match between the modeled and measured data at the USGS station in addition to the modeled and measured data at TtNUS Station 8. Of note is the difference in the modeled average flow for Station 8 when compared with measured flow at TtNUS Station 8 (25.61 cfs) versus measured flow at the USGS Station (24.84 cfs). The reason for this difference is because only modeled data for times when the corresponding measuring station was operating is included in the average. In other words, there were some gaps in the TtNUS Station 8 record due to equipment malfunctions. The modeled data average corresponds to times when the TtNUS Station 8 was operating properly. This time period is different than the times when the USGS Station was operating. So the modeled averages for Station 8 correspond to two different time periods: one time period corresponding to times when TtNUS Station 8 was operating properly and another time period when the USGS Station was operating properly. Of interest is that the correspondence between the two measured values, USGS station and TtNUS Station 8, were within 19 percent of one another. Please refer to section 3.2.2.1 of TtNUS 2005 for more details of this comparison.

Additional flow statistics evaluated included histogram plots (Figure 5-1) and flow at various percentile values (Table 5-8). For the most part, the histogram plots indicate that the distribution of flow between the modeled and measured data were similar with the exception of Station 5 for which the frequency of occurrence of the extremely low values (0 – 5 cfs) was lower for the modeled data than for the measured data. For the second bin (5 cfs to 15 cfs) the model over estimated the frequency of occurrence over that for the measured values. This discrepancy is observed in the percentile values (Table 5-8 and inset in Figure 5-1), which emphasize the constant value set for measured flow at Station 5 during low flow events (2.52 cfs). This occurrence was due to the rating curve established for this station which was extremely flat. At very low flow conditions, the measured flow was insensitive to water level. Only at higher flows was a relationship observed between measured water level and measured flow. The lack of relationship at very low flows was observed at other stations and from the percentile plots is especially apparent for Station 1. The percentile values also emphasize that the model simulates larger variations in flow at the very low flow values, whereas these variations were not captured by the measured data.

Time series plots for Station 4 (Top of Figures 5-2 and 5-3) and Station 8 (Top of Figures 5-4 and 5-5) show that the model is capable of capturing the streamflow pattern very well. When measured flows were high, the model also simulated high flows and vice versa. For Station 4, the measured data is characterized by more rounded peaks than those simulated by the model. Of interest are the double peaks that are observed in both the measured and modeled data for Station 4 for the month of September 2002 (Figure 5-3). The time series plots for Station 8 include the modeled values (solid blue lines) and the measured values from both the USGS Station (long green dashes) and from TtNUS Station 8 (short red dashes). As observed from these plots, all three values match up reasonably well. The patterns between all three values were very similar, including the shapes of the peaks. Of note are the two small random peaks in streamflow that were observed at the USGS and TtNUS monitoring stations during September 14 and 25, 2002. These random peaks occurred during times of no rain (which is noted by the "x" on an inverted axis on those plots) and were thus not simulated by the model. These random peaks are generally infrequent throughout the record and are believed to be due to releases from the Winchester Falls Dam or the Horn Pond Creek dam located upstream of Station 8.

5.2.2 Dissolved Metals Model

The dissolved metals portion of the model performed very well with average modeled versus measured dissolved metals concentrations for the composite samples within 1 µg/L for As, Cr, Cu, and Pb and within 0.02 mg/L for Fe (Table 5-10). For the grab samples, modeled versus measured dissolved As, Cr, Cu, and Pb were generally within 1 µg/L and dissolved Fe within 0.5 mg/L, with the exception of Stations 6 and 7 where the mean measured dissolved arsenic concentration was over-estimated by about 2 to 3 µg/L. The dissolved arsenic values for Stations 6 and 7 could not be lowered for the grab sample (baseflow samples) because the concentrations assigned to the slow and longterm baseflow components for the corresponding modules was zero or very near zero. Time series plots of dissolved arsenic concentration for Station 4 (top of Figures 5-6 and 5-7) and Station 8 (top of Figures 5-8 and 5-9) indicate that the model performed reasonably well with modeled (solid line) and measured (open circles) within the same order of magnitude.

5.2.3 Suspended Sediment Model

Mean modeled suspended sediment concentrations were within 1.5 mg/L of the measured values for all stations except for the grab samples for Station 4 which were within 2 mg/L, the grab samples for Station 7 which were within 3 mg/L, and the composite samples at Station 2 which were within 4 mg/L (Table 5-11 and 5-12).

The correspondence between the means for Station 4 is considered to be reasonable given that the results consider samples collected during both storm flow and baseflow conditions. Also a significant amount of variability in suspended sediment concentrations was noted at Station 4 during baseflow conditions. This variability was not effectively captured by the model and suggests that the existing algorithms based upon the simulation of quick, slow, and longterm baseflow sediments that work well for all other modules, are not capable of reproducing this variability. Apparently the mechanisms of sediment transport between Stations 2 and 4 different than the mechanisms governing other portions of the river during baseflow conditions. Strong efforts were made to develop a conceptual model which would capture this variability, including an evaluation of possible correlations with seasonal changes and water/air temperatures, but distinct relationships were apparent such that a model could be established to capture this variability with the data that was available.

The measured average value of the grab samples at Station 7 was influenced by an elevated suspended sediment measurement (50 mg/L) measured during one occasion (July 14, 2001). Without this value the average of the grab samples for Station 7 would be equal to 4.6 mg/L which is very close to the mean of the modeled values (5.4 mg/L).

The larger modeled composite TSS concentration at Station 2 was due to the inability of the model channel (Channel A) which is very short, to attenuate the peak TSS concentrations from Station 1 which tends to be very “flashy” in its response. Currently, the HBHA is modeled as a channel, but it behaves more like an impoundment which would be capable of more effectively reducing the peaks in suspended sediment concentrations due to more efficient settling. A further refinement of the model would be to develop a new component which would more effectively account for setting the suspended sediments within impoundments. Generally the suspended sediment portion of the model captures the mean measured suspended sediment concentrations throughout the river

Time series plots for Stations 4 and 8 further support that the model performs well. In general when measured suspended concentrations are elevated, the model also predicts elevated suspended sediment concentrations (bottom of Figures 5-2 to 5-5). The suspended sediment during baseflow conditions on April 17 for Stations 4 and 8 (bottom of Figures 5-2 and 5-4) and on September 10 for Station 4 and 8 (bottom of Figure 5-4 and 5-5) were reproduced almost exactly by the model. For the storm events evaluated during these months, the model performed very well for the April 2002 events at both Stations 4 and 8 by closely simulating the peak concentration. The peak for the September storm was over-estimated by the model at Station 4 for the September 2002 storm. This over-estimation is due to the inability of the model to attenuate peak suspended sediment concentrations through the HBHA impoundment. Again, as mentioned above the model simulates these impoundments as channels when in actuality these features serve to more effectively remove the suspended sediment load during storm events. The declining suspended sediment concentration was simulated almost exactly by the model for Station 8 during the September 2002 storm. Overall, the suspended sediment model is considered to perform well with the exception of the over-estimation of peak concentrations during storm events immediately downstream of the HBHA.

5.2.4 Particulate Metals Model

As discussed in sub-section 5.1.4 the particulate portion of the model was calibrated indirectly against total metals concentrations. All of the modeled total iron concentrations were within 1 mg/L of the measured values, on average (Tables 5-13 and 5-14). The composite total metal concentrations (Table 5-14) were within 2 µg/L with the exception of chromium and copper for Station 2, and lead for Stations 2 and 7. For the grab samples, the calibration of the model was generally within 1 µg/L with the exception of Station 4, 8, and on occasion Station 7 (Table 5-13). The larger differences for Stations 4 and 8 was due, in part, to the fact that the grab samples for these stations correspond to both storm flow and baseflow conditions resulting in generally higher overall averages, and thus the differences between modeled and measured were also larger on an absolute scale.

The performance of the model on time series plots is illustrated at the bottom of Figures 5-5 through 5-8. For the April 2002, the initial peak arsenic concentration is over-estimated by the model at Station 4, however, the concentrations after this peak are simulated closely (Figure 5-5).

5.2.5 Arsenic Fluxes

Modeled versus measured arsenic fluxes are plotted in Figures 5-10 through 5-13. The top portion of these plots corresponds to dissolved arsenic flux and the bottom corresponds to total arsenic flux. As mentioned earlier, the flux was computed as the product of flow and concentration. If the measured flow value was missing then the measured flux is shown as a black circle. If the arsenic concentration was above the detection limit then the measured flux is shown as a red circle.

The time series plots (Figure 5-10 through 5-13) indicate that the model performed reasonably well at capturing some of the variability in arsenic fluxes. The measured data indicate a rising flux for total arsenic at Station 4 and 8 during the April 2002 event (bottom of Figure 5-10 and 5-13). This rise was simulated by the model. The model performed very well for the September 2002 event by capturing the magnitude and overall shape of the dissolved and total arsenic flux for Station 4 and the total arsenic flux for Station 8.

5.3 Sensitivity Analysis

Model runs for sensitivity analysis were based upon the optimized calibration run and then independently changing each of the optimized calibrated values. The optimized calibration values were either increased by a set increment or the values were set to an alternate value. Sensitivity was conducted on the primary flow calibration parameters (IAQ, IAS, IAM, KQ, KS, and KM) and for the primary suspended sediment calibration parameters for each module (Cs, maxlq, Cq, frac, and Cr) and for the primary suspended sediment parameter (Cs) used to simulate transport through the channels. For each sensitivity model run, a total of 27 output values (Table 5-15) were evaluated at each gauging station with the exception of Stations 4 and 8 for which 15 output values were evaluated due to the fact that only grab samples (no composites) were collected at these stations. As a result, each sensitivity model run resulted in 192 output values (27x6 + 15x2). The output values evaluated corresponded to those used to obtain the optimum calibration. Thus the output data evaluated corresponds to time periods for which measured data were available.

Each of the flow calibration parameters (IAQ, IAS, IAM, KQ, KS, and KM) were changed by a set increment (Table 5-16) for each module for a total of 48 sensitivity analysis runs for the flow parameters alone. Five suspended sediment calibration parameters (Cs, maxlq, Cq, frac, Cr) were evaluated for each of the 8 modules along with one calibration parameter (Cs) for each of the 6 channel components used in the model (Table 5-17) resulting in 46 model runs for the suspended sediment parameters. Given that 192 output values were evaluated per sensitivity model run, the sensitivity analysis included in this report resulted in the generation of over 18,000 output values. Only a subset of the results is presented in this section. The results in their entirety are provided in the electronic appendices (See the subdirectory called “Sensitivity”). Output was evaluated in terms of a percent change between the results obtained from the sensitivity model run versus the model run corresponding to the optimized calibration (eqn 5.1).

$$\%\ change = \frac{sensitivity\ run\ output - optimized\ \ run\ output}{optimized\ \ run\ output} * 100\% \qquad \text{eqn. 5.1}$$

Results from the sensitivity runs for the flow calibration parameters indicate that KQ and KS are the most sensitive of the parameters among the six evaluated (Table 5-18). Of note is the large impact of relatively small changes in the KQ value for Station 1 composite values. Secondary effects are observed at Station 2 for the composites and then at Station 4 for the grab samples (which include both baseflow and storm event samples). No impacts were observed at Station 3 given the change in calibration at Station 1, as expected, since Station 1 and Station 3 are entirely independent with respect to direct surface water contributions. Overall KQ and KS parameters affect the composites more so than the grab samples, except at Station 4. This observation is consistent with the formulation of the model since KQ and KS are parameters which are used to simulate storm generated flows. Grab sample data at Station 4 includes storm event data. The next most sensitive calibration parameters were IAQ and IAS which show intermediate impacts on modeled values at Station 1 and Station 4. Changes in IAM and KM, the snow melt flow parameters, essentially resulted in insignificant changes in the modeled values. This finding is consistent with the very small amount of snow during the TtNUS monitoring period and thus the impact of snowmelt parameters on the model should be very small.

Results from the sensitivity runs for the suspended sediment calibration parameters (Table 5-19) indicate that these parameters had no effect on flow and dissolved metals transport, as expected. Among the suspended sediment calibration parameters, maxlq and Cq were the most sensitive. Cs (for internal channels), frac, and Cr are the next most sensitive. The calibration for the external channels (e.g. Cs for Channel A) appears to not significantly affect the model. Of interest is the impact of the calibration parameters (Cs for internal channels, maxlq, Cq, frac, Cr) on the modeled “grab” values of Station 4 and for the composite samples for the remaining stations. Again, as emphasized above, the grab sample data for Station 4 includes storm event results. Of interest is that the change in calibration parameters affect modeled values primarily at Station 1 and then secondarily at Station 2 and so on in the downstream direction. Station 3 is not affected since flows at this station are independent of flows at Station 1.

6.0 MODEL RESULTS - EXISTING CONDITIONS

Results are included for streamflow (Section 6.1), dissolved metals (Section 6.2), suspended sediments (Section 6.3), and particulate metals (Section 6.4). Results are provided in terms of contributions from each module. Contributions are typically divided by the surface area of the module to provide a measure of the relative contribution per unit surface area.

Furthermore, it is emphasized that the results presented herein are modeled results which were calibrated against measured data. The model was subject to some discrepancies with the measured data, and so the model output should be interpreted with this in mind. The developer of the model estimates that the results provided below are “order-of-magnitude” estimates.

6.1 Streamflow

The average flow rate from the Aberjona River for the 18-month TtNUS period of record was 25 cfs. This value is consistent with the 30 cfs value that was observed for the entire period of record (1939 to 2002), especially since the TtNUS period of record spanned two summers which is when flows are typically at their lowest. Although the Woburn West Module is the largest module contributing water towards the Aberjona River, it provides the smallest quantity of water on a per unit area basis (0.8 cfs/mi^2) (Table 6-1). This is consistent with the extensive network of groundwater withdrawals from this Module and with the presence of large reservoirs which permits for more extensive evaporation of water. The module that provides the greatest quantity of water on a per unit area basis (2.7 cfs/mi^2) is Module 8 which incorporates the highly urbanized area of Winchester. Longterm baseflow is generally the largest contributor of flow from each module. Flow from the slow system (storm induced groundwater flow) is typically the second largest contributor. Quick flow contributions (surface runoff and inflows from storm sewers) are significant from Module 8, representing roughly 40 percent of the flow contribution.

6.2 Dissolved Metals

The overall dissolved metals contributions from the Aberjona River during the TtNUS period of record are estimated at 7.0 g/hr, 820 g/hr, 5.2 g/hr, 10 g/hr, 11 g/hr, 0.14 g/hr for arsenic, iron, chromium, copper, lead, and mercury, respectively (Tables 6-2 to 6-7). The highest drainage area – normalized dissolved arsenic fluxes came from Module 2 (Table 6-2). The next highest was from Module 8. Modules 2 and 3 collectively accounted for almost 70% of the dissolved arsenic flux. Longterm baseflow and slow storm flows were responsible for the bulk of the dissolved arsenic flux. Quick flow was responsible for the transport of the bulk of the contribution (although small) from Module 6.

The highest drainage area – normalized dissolved iron fluxes came from Modules 2 and 4 (Table 6-3). The next highest was from Module 8. Longterm baseflow carried the bulk of the dissolved iron for Module 3 and 4. Quick flow was the most significant contributor for Modules 5, 6, and 7. Dissolved iron contributions were roughly equal among the different components for Module 2.

Station 2 was also characterized by a high drainage area – normalized dissolved metals flux for chromium and copper (Tables 6-4 and 6-5). Station 4 had high drainage area – normalized dissolved metals fluxes for lead and mercury, relative to the other stations (Tables 6-6 and 6-7). Station 8 also was characterized by a high drainage area normalized dissolved lead contribution. Slow storm flow and longterm baseflow carried the bulk of the remaining dissolved metals (chromium, copper, lead, and mercury) for all the modules, with the exception of Modules 7 and 8 which had significant contributions from the quick component.

6.3 Suspended Sediments

According to the model, the total suspended sediment flux from the watershed is roughly 54 kg/hr, on average. Modules 1 and 6 were characterized by the largest drainage area normalized fluxes of suspended sediments (Table 6-8). Modules 2, 4, and 5 and the Woburn West sub-basin were characterized by the least. The majority of the suspended sediment is carried from each module by the quick flow system. For Module 4, slow and longterm baseflow play a significant role given that there is relatively little quick flow from this module. Channel sediments (which are previously deposited sediments from either quick, slow, or longterm baseflow systems) are significant contributors to the sediment flux for Modules 1, 6, and 8.

6.4 Particulate Metals

The overall particulate metals contributions from the Aberjona River during the TtNUS period of record are estimated at 33 g/hr, 8000 g/hr, 41 g/hr, 86 g/hr, 72 g/hr, 0.8 g/hr for arsenic, iron, chromium, copper, lead, and mercury, respectively (Tables 6-9 to 6-14). Comparing these results with the results for dissolved metals indicates that the bulk of the metals are carried by the particulate phase.

Module 2 had the largest drainage area normalized particulate arsenic flux (Tables 6-9 and 6-10). The value (25 g/hr) was higher than fluxes for the other modules by over an order of magnitude in most cases. For Station 2, the slow component (which represents a storm induced groundwater contribution) was the primary contributor to the arsenic and iron particulate fluxes.

High chromium and copper particulate fluxes (drainage area normalized) were observed for Modules 5, 6, and 8. Module 7 was also elevated for normalized particulate copper. Module 6 was characterized by relatively high lead and mercury particulate fluxes (drainage area normalized).

7.0 SCENARIO EVALUATION

Remediation scenarios for the Aberjona River watershed focused on minimizing metals transport from the upper reaches of the river, in particular from the HBHA. Two primary designs were under consideration. These designs included a cofferdam located upstream of Station 2 midway within the HBHA. The purpose of the cofferdam was to maintain the chemocline (Ford 2002) and increase the residence time of waters known to contain higher arsenic concentrations. The plan was to divert storm flows from Halls Brook (which was characterized by relatively low arsenic concentrations) downstream of the cofferdam to minimize the disturbance of the chemocline during storm flow conditions. Storm induced flows between Station 1 (Halls Brook confluence) and upstream of the cofferdam would flow into the retention area upstream of the cofferdam thereby increasing the residence time of these waters to promote precipitation and settling of the arsenic contributed by this area. During baseflow conditions aerated waters from Halls Brook would enter upstream of the cofferdam for purposes of maintaining the chemocline within the HBHA. The cofferdam thus would serve to encourage the removal of arsenic from waters entering the HBHA between Stations 1 and 2. The second design under consideration was a reactive wall. This reactive wall would intercept groundwater flows from areas contributing directly to HBHA (between Stations 1 and 2) thereby removing the majority of the arsenic within the corresponding groundwater. This section describes the results from various runs designed to evaluate the impact of these different designs on arsenic transport downstream. Details concerning the inputs corresponding each scenario run are included (Section 7.1) along with the results (Section 7.2) and limitations of the model (Section 7.3).

7.1 Input Used to Evaluate Possible Remediation Designs

The results from the optimized calibration run are referred to as “existing conditions.” The input used to evaluate the various scenarios was the same as that corresponding to “existing conditions” with the exception of arsenic concentrations assigned to each flow and suspended sediment component. The parameters used to control the quantities and timing of the water flow and suspended sediments remained the same between the “existing condition” model run and the runs designed to simulate the impacts from the different remediation efforts. Possible metals reductions of the two proposed remediation designs were evaluated through four scenario runs. Three scenarios were run to simulate possible metals reduction associated with the cofferdam and one scenario was run to simulate possible metals reduction associated with the removal of contaminants from groundwater discharges by either a groundwater extraction and treatment system or a permeable reactive wall. The model was also run for the entire TtNUS period of record (May 15, 2001 to October 29, 2002) and statistics were compiled for the entire period of record and for a storm event for comparative purposes to a baseline condition assuming no remediation occurs. The scenarios evaluated were as follows:

1) "Existing Conditions" taken directly from the model after calibration. (No remediation performed)

2) "Cofferdam, Baseflow" which assumes that the concentration of metals passing the cofferdam during storm flows were equivalent to the concentrations at Station 2 during baseflow conditions. This was accomplished by decreasing the baseflow particulate concentration at Station 1 (Module 1) by 75 percent and then setting the storm metal concentrations from Module 2 to baseflow values for both dissolved and particulate phases.

3) "Cofferdam, 50&75 percent" which assumes that the cofferdam only affects the particulate phase by removing 75 percent of the particulate metals upstream of Station 1 during baseflow conditions and 50 percent of the particulate metals upstream of Station 2 during storm conditions and 75 percent of the articulate metals upstream of Station 2 during baseflow conditions.

4) "Cofferdam, Optimum" which assumes a 75 percent decrease in the particulate metal contributions from Module 1 during baseflow conditions. In this case the metal concentrations from Module 2 are substituted with the dissolved and particulate values corresponding to Module 1 for storm and baseflow conditions.

5) "Reactive Wall" which assumes that all contaminated groundwater discharges are removed, sets the dissolved and particulate metals for the slow and long-term baseflow components for Module 2 equal to Module 1 values.

The changes to the flow and suspended sediment metals contributions are shown in Table 7-1. Dissolved arsenic concentrations remained the same for Module 1 (Halls Brook contribution) for all of the scenarios evaluated. Particulate arsenic concentrations for sediments from Module 1 remained the same except for the cofferdam scenarios which assumed a 75 percent reduction in the particulate arsenic from Module 1 during baseflow conditions. The major differences in model input were observed for metals concentrations assigned to contributions from Module 2. The optimum cofferdam scenario assumes that the metals contributions downstream of Station 2 would correspond to concentrations observed at Station 1. In other words, the cofferdam would serve to reduce the arsenic concentrations to background levels as observed at Station 1. As a result of this assumption, the metals concentrations (dissolved and particulate) for Module 2, were set to Module 1 values. The "baseflow cofferdam" assumes that the metals concentrations from Module 2 during storm flow conditions would be equivalent to concentrations transported during baseflow conditions. As a result the arsenic concentration associated with the quick and slow components of flow and suspended sediments were set to baseflow values. The "50&75" cofferdam scenario assumes that the cofferdam only affects particulate metals. During storm events the particulate metals concentrations originating from Module 2 would be reduced by 50 percent and during baseflow conditions the particulate metals from Module 2 would be reduced by 75 percent. This scenario also assumes a 75 percent reduction in the baseflow metals concentrations originating from Module 1, since the majority of the water from this module will be assumed to pass over the cofferdam during baseflow conditions. The reactive wall scenario is assumed to only affect metals concentrations for groundwater components originating within Module 2. These groundwater components include both the slow and long-term baseflow components of flow and suspended sediments. For these components the metals concentration are set to background values, as given by the concentrations associated with the same components from Module 1. The quick flow and particulate components were kept the same as that for existing conditions since it was assumed that these components (primarily surface runoff) would not come in contact with the reactive wall.

7.2 Results

As mentioned above, each scenario was run for the TtNUS period of record (May 15, 2001 to October 29, 2002). Two different sets of results were extracted from these model runs. The first corresponded to results for the entire period of record and the second corresponded to a 2.8 inch storm that occurred during May 2002 storm. The specific dates and times corresponding to the extracted storm data was May 12, 2002 at 12:00 to May 16, 2002 at 23:00.

The purpose of extracting the storm data was to evaluate differences in possible metals reductions between storms versus the period of record as a whole and to evaluate the effectiveness of various remediation scenarios as well as the selected location of the remediation area. The results were evaluated to determine possible reductions for the entire TtNUS period of record for arsenic flux (Figure 7-1; Tables 7-2 to 7-6) and arsenic concentration (Figure 7-3; Tables 7-2 to 7-6) at each station. The arsenic flux (Figure 7-4) and concentrations (Figure 7-6) for the May 2002 storm was graphed and tabulated separately (Tables 7-7 to 7-11). The results were also normalized by the contributing area to each station (Figures 7-2, for the entire TtNUS period of record, and Figure 7-5, for the May 2002 storm), to further evaluate the effects of drainage area on metals reductions.

Overall, the predictions for the “Cofferdam, Baseflow” and the “Cofferdam, 50&75 percent” were very similar for both time periods evaluated. The arsenic flux and concentration decreases for the “Cofferdam, Optimum” and “Reactive Wall” were also very similar. The predicted decrease in flux at Stations 2 and 4 were as high as 90 percent for the more aggressive scenarios. This translates to about at 25 percent reduction in flux at Station 8 at the outlet of the watershed when considering the entire TtNUS period of record and about a 20 percent reduction in flux if only the May 2002 storm is considered. When normalizing the results by contributing area, the relatively large normalized contribution at Station 2 is greatly reduced by the more aggressive scenarios. In summary the “normalized” plots emphasize that the optimum location for remediation is upstream of Stations 2 and 4, given the large amount of arsenic contributed by the upstream areas relative to the volume of water.

7.3 Limitations of Model

Important limitations of the model worth mentioning are that the model does not consider changes in arsenic contributions in the long term. Once the primary arsenic source is removed, the river will tend to flush out metals, the river will generally become cleaner over time, and the metals contributions from the downstream modules will decrease. The model does not account for this long term decrease. Also, given the manner in which the scenarios were handled (simply changing the metals contributions associated with flow and suspended sediment components from Modules 1 and 2) the model does not simulate the changes in the quantities or distribution of flow and suspended sediments transported downstream due to the presence of the cofferdam and reactive wall. Essentially the scenarios were evaluated by changing the arsenic concentrations of the flow and suspended sediment components and the amount of bulk water and sediment transported downstream remains the same. The only change is the arsenic concentration of the water and sediment transported. In reality, the cofferdam could significantly decrease bulk suspended sediment transport from areas upstream of Station 2. This decrease in bulk suspended sediment transport is not considered by the model. Also, the cofferdam and possibly a groundwater extraction system which discharge treated effluent into the HBHA, could cause local increases in water levels which may alter the net movement of water. This is particularly relevant in the vicinity of the cofferdam which would result in increased surface water levels. These increased surface water levels will likely encourage a greater loss of this surface water towards groundwater. The model does not simulate this effect. Therefore, overall, the model is believed to be generally conservative. If the limitations in the model were to be addressed, it is likely that removal of arsenic from the Aberjona River Watershed would be greater than that predicted with the current model. Thus, it is likely that a greater reduction of arsenic would be observed in downstream areas than that predicted by the current model.

8.0 SUMMARY AND CONCLUSIONS

An extensive effort was placed in developing a model (Section 8.1) for simulating flow, suspended sediment, and metals transport through the Aberjona River watershed. This model was extensively calibrated and the performance of the model was evaluated using many different criteria including a sensitivity analysis (Section 8.2). Once calibrated the model was used to simulate possible impacts on arsenic transport from the different scenarios proposed to remediate arsenic contamination within the upper reaches of the Aberjona River watershed (Section 8.3).

8.1 Formulation of Computer Code

The computer code utilized for this study, TtNUS-AWM, was a modification of an earlier code developed through MIT during the early 1990's. The primary updates to the code included the re-organization of the code to accommodate geometry of the Tetra Tech monitoring network, the addition of a module to account for losses of water as a function of water depth, and the addition of two additional metals to the code, lead and mercury, in addition to arsenic, iron, chromium, and copper. The geometry of the TtNUS monitoring network was accommodated by separating the watershed into a series of modules, each module corresponding to the surface area of the watershed that drains directly towards a particular monitoring station. Streamflow from each module within the watershed was modeled as the sum of three different flow components, a quick component associated with direct runoff and storm sewer inputs, a slow component which is a storm induced groundwater flow component, and longterm baseflow which represents the baseline groundwater input to the river. Dissolved metal fluxes were modeled by assigning each flow component a dissolved metal concentration. Sediments were assumed to be transported with each flow system. Sediment transport for the quick system was modeled through a build-up and wash-off mechanism. Slow and longterm baseflow sediments were modeled by a low but constant suspended sediment concentration. Once the sediments enter the channel, the model checked for possible deposition and erosion. Particulate metal fluxes were modeled by assigning each suspended sediment component a particulate metals concentration in units of mass of metal per mass of sediment. The model requires hourly rainfall and air temperature as its input. Over 250 output files were generated describing flow, suspended sediment, and metals concentrations and fluxes at different points throughout the watershed. The model was run for the TtNUS monitoring period from May 2001 to October 2002.

8.2 Model Performance – Existing Conditions

The model was found to perform very well in simulating flow and dissolved metals transport. Overall the model predicts that the majority of the water entering the Aberjona River comes from the longterm baseflow component. Suspended sediment transport from the watershed was estimated at 54 kg/hr on average with the majority originating from the quick flow system or from the erosion of sediments that were previously deposited within the channel. These deposited sediments can originate from either quick, slow, or longterm baseflow systems. Total metals transport at the outlet of the river was estimated at 30 g/hr, 7000 g/hr, 34 g/hr, 81 g/hr, 63 g/hr, and 0.8 g/hr for arsenic, iron, chromium, copper, lead, and mercury, respectively, for the TtNUS monitoring period. According to the model, over 70 percent of the arsenic observed in the river originates within Modules 2 is located in the northern part of the watershed.

8.3 Scenario Evaluation

A total of four scenarios were evaluated for possible reductions in arsenic transport within the Aberjona River due to remedial actions. These scenarios were compared to a model run of existing conditions. Three of the scenarios were focused at placing upper and lower bounds on a “cofferdam” scenario and the fourth scenario was focused at evaluating the groundwater treatment scenario where all contaminated groundwater discharges were removed. Overall, the results indicate that both remediation scenarios can result in decreases in metals fluxes and concentrations within the river compared to existing conditions (Tables 8-1 to 8-4).

The performance of the “optimized cofferdam” scenario was comparable with that of the groundwater treatment/reactive wall scenario. Within these more aggressive scenarios, greater than 90 percent reductions in arsenic concentrations were simulated and between 86 percent and 91 percent reductions in flux were simulated for Stations 2 and 4 when the entire TtNUS period of record was considered. These reductions corresponded to a decrease in arsenic concentrations from 35 µg/L to 2 or 3 µg/L and decreases in arsenic fluxes from 9 to 15 g/hr to 1 or 2 g/hr. At Station 8, the model simulated between 34 percent and 35 percent reductions (from 7 µg/L to 4 µg/L) in arsenic concentrations and 23 percent to 24 percent reductions in arsenic flux (from 30 g/hr to 23 g/hr). When an individual storm event was considered (May 2002 storm), reductions were slightly lower but similar. At Stations 2 and 4 concentrations were simulated to be reduced by 89 to 92 percent, with concentrations decreasing at these stations from roughly 40 µg/L to 3 or 4 µg/L. Fluxes for the May 2002 storm were simulated with 87 percent to 90 percent reductions with a reduction from the high of roughly 80 g/hr at Station 2 to a value of roughly 8 g/hr. At Station 8 for the May 2002 storm, fluxes were simulated to be reduced by 18 percent (from 220 g/hr to 180 g/hr) and concentrations by 22 percent to 23 percent (from 18 µg/L to 14 µg/L).

REFERENCES

Chasen. S.H., 1978. Geometric Principles and Procedures for Computer Graphic Applications. Prentice-Hall, Inc., Englewood Cliffs, NJ. p. 15.

Chow, Ven Te., et al., 1964. *Handbook of Applied Hydrology; A Compendium of Water Resources Technology*. Mc-Graw Hill. New York.
Linsley, Ray K. Jr., et al., 1975. *Hydrology for Engineers. Third edition.* Mc-Graw Hill. New York.

Das, B.M., 1985. Principles of Geotechnical Engineering. PWS Publishers, Boston, MA.

Ford, R., 2002. *Natural Attenuation Study, Ground Water, Surface Water, Soil and Sediment Investigation, Industri-plex Superfund Site, Woburn, Massachusetts*. Office of Research and Development, National Risk Management Research Laboratory, U.S. EPA, Ada, OK.

Legates, D.R., and McCabe, G.J., Jr., 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resources Research, 35(1): 233-241.

McCuen, R.H., 1989. *Hydrologic Analysis and Design*. Prentice Hall, New Jersey.

Overton, D.E. and Meadows, M.E., 1976. Stormwater Modeling. Academic Press, New York.

Rao, S. S., 1996. Engineering Optimization, Theory and Practice. John Wiley and Sons, Inc., New York, New York. p. 350-353.

Solo-Gabriele, H.M., 1998. “Generation of a Long-term Record of Contaminant Transport. “ *Journal of Environmental Engineering*, 124(7):619-627.

Solo-Gabriele, H.M., and Perkins, F.E., 1997a. “A Watershed-Specific Model for Streamflow, Sediment, and Metal Transport. “ *Journal of Environmental Engineering*, 123(1): 61-70.

Solo-Gabriele, H.M., and Perkins, F.E., 1997b. “Streamflow and Suspended Sediment Transport in an Urban Environment. “ *Journal of Hydraulic Engineering*, 123(9): 807-811.

Solo-Gabriele, H.M., and Perkins, F.E., 1997c. "Metal Transport within a Small Urbanized Watershed. " *Journal of Irrigation and Drainage Engineering*, 123(2): 114-122.

Solo-Gabriele, H.M., 1996. "Metal Flux Estimates for the Aberjona River. " WEFTEC'96, *Proceedings of the Water Environment Federation 69th Annual Conference & Exposition, Dallas, TX*. Volume 4: 293-304.

Solo, H.M., 1995. *Metal Transport in the Aberjona River System: Monitoring, Modeling, and Mechanisms*. Massachusetts Institute of Technology, Cambridge, MA., Ph.D. Dissertation.

Tetra Tech NUS (TtNUSa), January 2005. Draft Evaluation of Flow, Suspended Sediment, and Heavy Metals in the Aberjona River prepared for the Remedial Investigation/Feasibility Study. Tetra Tech NUS, Inc., Wilmington, MA.

Tetra Tech NUS (TtNUSb), March 2005. Draft Final MSGRP Remedial Investigation Report. Tetra Tech NUS, Inc., Wilmington, MA.

Vanasse Hangen Brustlin, Inc. (VHB), 2003. Middlesex Canal/Halls Brook Hydrologic/Hydraulic Analysis. VHB, Watertown, Massachusetts. Prepared for the U.S. Army Corps of Engineers, Concord, MA.

APPENDIX A

MODEL REVIEW BY WATERMARK INC.

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May 25, 2005

Gordon Bullard
Tetra Tech NUS, Inc.
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Wilmington, MA 01887

RE: Aberjona River Sediment Transport Model Review

Dear Mr. Bullard:

In accordance with Subcontract No. 1001689, Watermark has prepared the following letter regarding a review of the Aberjona River Sediment Transport Model prepared by Dr. Helena Solo-Gabrielle. This review has been conducted to provide third-party verification of the subject model as recommended by the U.S. Environmental Protection Agency. This review included an evaluation of the modeling framework, input/output data, calibration procedures, model code, and reproduction of results. The following materials/documents were included in the review: 1) Dr. Helena Solo-Gabrielle's thesis and articles, 2) *Interim Remedial Investigation /Feasibility Study, Industri-Plex Site, Woburn, Massachusetts*, dated June 2003 (Interim June 2003 Report), 3) *Draft Evaluation of Flow, Suspended Sediment, and Heavy Metals in the Aberjona River*, dated January 2005, and 4) model source code (dated March 1, 2005). The remainder of this letter presents an overview of the review, findings, summary and recommendations.

Overview

The Aberjona River Sediment Transport Model is a watershed specific model originally developed by Dr. Helena Solo-Gabriele for her PhD dissertation in 1995. The entire modeling framework was developed based on monitoring data from 1991 to 1993. In order to account for spatial variability, the watershed is sub-divided into modules (overland) and channels (for routing) for modeling various hydrological processes.

The four major subroutines of the model code were checked and verified to evaluate whether theoretical sediment transport concepts were implemented correctly. The subroutines that were evaluated included:

- wn – the subroutine that computes flow hydrographs;
- ss – the subroutine that computes suspended sediment mass and concentrations;
- met – the subroutine that simulates metal fluxes; and
- rt1 – the subroutine that routes flow, sediments and metals using Muskingum method.

In addition, unit conversions in the four major subroutines were checked and found to be implemented properly and consistently. The code was executed with the input data provided and reproduced similar results as presented in the Interim June 2003 Report. The main advantage of the model is in the simplicity of construction based on observed processes. Overall, it is a good screening level model which will help in understanding the major hydrological and water quality processes within the watershed. Note that the model is limited in its ability to simulate extreme events (outside of model observed events during the model construction period). This should be taken into consideration when modeling extreme events and evaluating various remediation scenarios.

Findings

The major findings from the review of the model are presented below:

1. Based on the observations from the 1991 to 1993 monitoring data, the total flow was assumed to consist of three components: quick storm flow, slow storm flow, long-term base flow. The melt flow during the winter months is added to slow storm flow (40%) and quick storm flow (60%). The unit hydrographs for quick, slow, and melt flows derived at Station 8 during 1992 is the major driver for modeling the watershed hydrology. The same unit hydrographs are being used in the current study for all of the modules. The fraction of effective rainfall contributing to each flow is controlled by model parameters kq (quick storm flow), ks (slow storm flow) and km (melt water).

   The assumption implicit in using the same unit hydrographs is that all the modules are hydrologically behaving in the same way as the original watershed at Station 8. However, in the current study, Module 2 and Module 4 have different shape and hydrological characteristics than other modules. Hence, the unit hydrograph characteristics (especially for quick flow component) such as "time to peak" and "time of concentration" would be different accordingly. Since flow is one of the most sensitive parameters to compute sediment/metal loadings into the river, it is recommended that the unit hydrographs (quick, slow and meltflow) be verified for all the modules, especially Modules 2 and 4. In addition, the unit hydrographs from other modules should be compared with Module 8, from which the model was constructed.

2. Sediment is allowed to build up within each module by adopting the EPA Storm Water Management Model (SWMM) model approach. These sediments are then washed off to the main channel during quick flow and rainfall events. The sediments associated with slow storm and baseflow are modeled using a regression relationship developed from the 1991 to 1993 study period. A power function equation with velocity raised to the power four is used for the erosion of sediments from the build-up area to the channel, based on the assumption that most of the sediments which are transported are cohesive.

The power function equation should be used with caution, because it is valid only within a range of particle sizes. The particle size distribution of sediment for the three flow components should be verified before using the power function equation.

3. Based on the transport capacity of the channel within each module, the sediment is either eroded or deposited. [Note that these channels are considered different from the channels used in the model for routing water, metals and sediment from module to module]. The sediment eroded from the channel comes from deposition of quick, slow and long-term baseflow sediments during prior times due to lack of transport capacity. If no deposition is left in the channel due to prior storm flow, then no additional channel erosion is simulated. Hence, it appears that channel erosion is not accounted for within the module.

   Sediment from channel erosion could be a major portion of total sediment in the watershed, as high as 60%, depending upon the condition of the channels. If the channels in this watershed are lined or concrete channels, then this mechanism is a non-issue. However, if they are natural channels, then channel erosion should be accounted for.

   Another observation is that a regression relationship developed during the 1991-1993 study at Module 8 is used to check the transport capacity for all the modules. Regression relationships should be used with caution in places other than for which it was originally derived.

4. Water and sediment are routed through connected channels using the Muskingum routing method. Transport capacities of the channels are checked at the end of each channel to determine erosion or deposition. Again similar regression relationships are used to check the transport capacity of the channel. Regression relationships should be used with caution in places other than for which it was originally derived.

5. Metals in dissolved and sorbed phase are modeled separately. No interaction is assumed between solute and sorbed phase of the metals. Metals are transported in dissolved phase with all three flow components along with the sediment of the three flow components. However, this it is indirectly accounted for by six different metal concentration parameters, three each for dissolved and sorbed phase transport associated with three flow components.

6. The calibration parameters (Tables 6.3 and 6.4 of the Interim June 2003 Report) used in this model are unique to the model. Therefore, it is difficult to verify whether or not these parameters are within reasonable ranges of literature values. Note that literature values are available regarding the partition of metals between solute and sorbed phases which could be used to verify some of the calibration parameters related to metals.

7. The model is calibrated first for flow, then sediment and finally metals. The calibration parameters listed in Tables 6.3 and 6.4 of the Interim June 2003 report are adjusted until acceptable calibration is achieved.

   The report doesn't elaborate on how the calibration was considered adequate (for e.g. $R^2 >$ 0.8 or mean square error less than 10%). The R^2 value for flow is low (0.5 to 0.6) for the upstream Modules 1, 2, & 4 which is the most contaminated portion of the watershed.

   Also, flow is under-predicted in the upstream modules by as much as 48% (in Module 2) and over-predicted in downstream modules by as much as 10%. It is essential that the flow is well-calibrated at the upstream modules. Otherwise more uncertainty will be introduced in sediment and metal loading from each module.

8. The model is consistently under-predicting the sediment (20 to 50%) in all of the modules, except for Module 4 where it is over-predicting (79%). Modules 1, 2, 3 and 4 have the highest error in suspended sediment loading (> 45%). It is imperative that flow and sediment calibration be improved to reduce the uncertainty in the particulate metal loading, as most of the loading seems to be coming in particulate form.

9. The concentration of dissolved arsenic associated with quick, slow and long term baseflow seems to be progressively decreasing from quick flow to baseflow for all of the modules except for Modules 3 and 8. In Modules 3 and 8, for baseflow dissolved arsenic has the highest concentration (Table 7.2). This should be analyzed further for accuracy and assessment of contaminated ground water entering the stream.

Summary and Recommendations

In summary, the main advantage of the model is its simplicity. In addition, it is a good screening level model which will help in understanding the major hydrological processes in the watershed. However, its ability to simulate extreme events and evaluate remediation scenarios needs to be scrutinized intensively. Here are some recommendations that will provide additional points for assessment of the model and increase the confidence in the use of the model for its intended purpose.

1. A sensitivity and uncertainty analysis of the model parameters should be performed to provide a confidence interval on the prediction of the model. In addition to model parameter sensitivity analysis, a sensitivity analysis on the input rainfall would also provide a measure of the model's response to some extreme events (e.g. what is the difference in metal accumulation at Station 8 when simulating a one in five year event compared to that of a one in 100 year event?);

2. For evaluating the model's flow simulation, in addition to R^2, using a Nash-Sutcliff coefficient of efficiency and index of agreement statistics is important, as they give a better measure of model performance than R^2 alone;

3. Only a few of the event concentrations were plotted. Hence, it is difficult to visually access how the model performed for the entire modeling period. Therefore, for comparing measured and modeled concentrations, it is recommended that a box plot of median, 25th and 75th percentile of observed data and model data for each module be used which is based on all the data during the observed period. This will help highlight whether the skewness/distribution in modeled and observed data is similar or different;

4. Module 4 seems to be of unique characteristic with the wetland as a major component and introduces considerable uncertainty in the prediction of flow/sediment/metals in downstream modules. Since flow was measured at Module 4 continuously, it is better to use the measured flow data at Module 4 and route it through the channels and the rest of the modules and parameterize (re-calibrate) other modules for flow. This would eliminate the uncertainty associated with Module 4 and help improve estimates of flow on the downstream modules. By using the measured flow data in the Module 4, Modules 1, 2 and 4 need not be modeled; and

5. If the intended purpose of the model is to evaluate remediation scenarios, it would be helpful to describe how the model parameters are going to be adjusted and what assumptions are going to be used for accurately representing various scenarios.

We thank you for the opportunity to review the model and hope the comments and recommendations will be helpful in applying the Aberjona River Sediment Transport Model. If you have any questions or comments regarding this letter, please do not hesitate to call either of the undersigned at (978) 452-9696 or (979) 845-5069 respectively.

Sincerely,

Olaf Westphalen, PG, LSP
Project Manager

Dr. Raghavan Srinivasan
Senior Scientist

cc: Joe Spangenberger (Watermark)
Dr. Helena Solo-Gabrielle (Solo Gabrielle Environmental LLC)

Response to Reviewer Comments Dated May 12, 2005

Response Written by H. Solo-Gabriele

Response Date: May 27, 2005

Comments were provided in three sections. These section are: Overview, Findings, and Summary/Recommendations.

Overview

Comment: ….. Note that the model is limited in its ability to simulate extreme events (outside of model observed events during the model construction period). This should be taken into consideration when modeling extreme events and evaluating various remediation scenarios.

Response: The author of the model agrees. As mentioned the model is intended to be used as a screening tool and the information obtained from it should be utilized in conjunction with additional information (in particular with directly measured data) to make final decisions concerning remediation scenarios.

Findings

Response to Comment Item #1 (Unit hydrograph characteristics): The author agrees that the net response observed in the river at Stations #2 and #4 are different but these differences can be accommodated through the model calibration parameters which control the relative contribution of the quick versus slow storm waters. For example, a "peakier" response would be controlled by increasing the amount of water observed by the quick system of a given module by decreasing IAQ and increasing KS. Overall in the updated model calibration included in the current 2005 report, flows at Station #2 and #4 were observed to perform significantly better given the addition of a module which now accounts for losses of water between Stations #2 and #4. However, the author of the model agrees that it is worth rechecking the validity of the unit hydrographs, if time and resources were permitting. If this model were to be further improved, re-evaluation of the unit hydrographs would be one of the areas that should be prioritized.

Response to Comment Item #2 (Power function and range of particle sizes): Data corresponding to the range of particle sizes of material transported in the river is very limited and thus a relationship based on particle size distribution cannot be developed from the information that is available. From experiences collecting samples during the 1991-1993 time period, particle size of material carried in the river is very fine and generally cohesive, as observed by "clumping" of the sediments at the bottom of sample bottles. The amount of sediment carried by the river is also very low and is generally "supply" limited. The model simulates this supply through a build up and wash off mechanism. Build up and wash off is controlled through a series of calibration parameters and in general the model fits measured data within reason. The use of the power function appears to work well. Furthermore, during extremely low flows the suspended solids concentrations were observed to decrease (below the baseline of 5 mg/L) during extremely low flows during the 1991 to 1993 period of record. This observed decrease was not observed in the 2001-2002 data presumably because deposition was not occurring or because of the manner in which the samples were collected. During 1991-1993 samples were collected through in-line filtration in the field which allowed for the filtration of large volumes of water (many liters) during times when suspended sediment concentrations were very low, thereby increasing the sensitivity of the measurement during extremely low flow conditions. During the 2001 to 2002 period, a constant water volume was used for measuring suspended sediment concentrations and this may have affected the sensitivity of the measurement during extremely low flow conditions. Therefore, deposition at extremely low flow conditions was not observed in the 2001 to 2002 data set and as a result the TtNUS-AVM model was modified accordingly and does not consider deposition during these extremely low flow conditions.

If additional time and resources were available, the author of the model recommends further sampling to collect data concerning suspended sediment particle characteristics in the river during different flow conditions. Of interest would be to collect samples not only from the river but also to collect samples from storm sewers and groundwater which contribute to the river. Of interest would be to characterize the particle size of sediments from these various sources.

Response to Comment Item #3 (Sediment from bank erosion): The author agrees that in certain types of rivers, in particular natural rivers, bank erosion can be significant. The Aberjona River is an urban river, which is highly controlled and manipulated. Also the gradient of the river is relatively flat and not characterized by extremely steep slopes. Given the author's experience during the 1991 to 1993 period and visits to the watershed during the 2001 period, bank erosion was not noticeable. According to the measured data (TtNUS 2005), the sediment flux was measured at TtNUS Station #8 at 6.7 kg/hour under baseflow conditions and 468 kg/hour under storm flow conditions. Assuming, as a rough estimate, that the average flux over the course of a year is about 100 kg/hour, then the amount of sediment transported at Station 8 would be roughly 1 x 10^6 kg. The length of the main trunk of the Aberjona River from Station #1 to Station #8 is 8.2 miles. The mass of sediment corresponding to a 1 ft by 1ft by 8.2 mile stretch (assuming a porosity of 0.2 and a sediment density of 2.7 g/cm^3) is estimated at 3 x 10^6 kg. If 100% of the suspended sediments were to come from bank erosion then according to the rough numbers above, it would take about 3 years of river flow to erode a 1 ft by 1 ft cross-sectional area from the bank. If 10% of the suspended sediments were to come from bank erosion it would take 30 years to erode an equivalent area. Such erosion has not been noticeable to the author.

Response to Comment Item #3 (Regression relation to check transport capacity) and *Response to Comment Item #4* (Transport capacities checked at the end of each channel): The regression relationship was used only for estimating deposition during extremely low flows. However, since such deposition was not observed in the 2001-2002 data set, the deposition algorithm was removed from the model within the updated TtNUS-AVM version. Transport capacity on the rising limb of the streamflow hydrograph was developed from theoretical considerations (See Solo-Gabriele 1995, p. 687-698). The theoretical relationship developed is valid for all points observed at Station #8 with the exception of 1 data point (TSS=179 mg/L at a flow of 3.6 cfs during October 2002), which exceeded the theoretical transport capacity. The theoretical transport capacity was based upon limited data concerning particle size distribution of the bottom sediments at TtNUS Station 8. It would be of interest to re-derive the transport capacity relationship based upon additional particle size data of the bottom sediments at TtNUS Station 8. Also, it would be useful to recode the model to provide for a curvilinear transport capacity relationship versus a linear one. The curvilinear relationship would better approximate the theoretical transport relationship derived from theory.

Response to Comment Item #5 (Metals in dissolved and sorbed phase modeled separately): Yes, the author agrees with the comment concerning the separation of the dissolved and sorbed phases. The model does not simulate the exchange of metals between sorbed and dissolved phases. The model accounts for differences in the distribution between dissolved and sorbed phases by providing for a separate dissolved and particulate metals concentrations from each module for each of the flow components.

Response to Comment Item #6 (Literature values regarding partition of metals between solute and sorbed phases): The distribution of metals between the dissolved and particulate phases is a function of many different variables including the physical and chemical characteristics of the particles and of the water column. Furthermore, given the relatively rapid changes in sediment and metals concentrations entering the river during storm events, it is also conceivable that the chemical characteristics of the water column (including the distribution of metals) may not be in equilibrium. With that said, there are limits as to the maximum amount of metal that can be found within a solid. The highest metal concentrations observed were for iron and iron, for example, is typically transported as an iron oxide (e.g. $Fe(OH)_3$). The fraction of iron by weight within $Fe(OH)_3$ is 52% and this value represents the absolute maximum concentration of iron that can be found within the particulate phase. The maximum iron concentration utilized in calibrating the model was greater than this and this represents a limitation of the model.

Response to Comment Item #7 (Does not elaborate on criteria for adequate calibration): Three criteria used for model calibration: mass balance, R^2, and evaluation of time series plots. The calibration process in the most recent version was optimized through a mathematical optimization routine which was then checked against performance through time series evaluation. Adjustments were made to the mathematically optimized parameters after review of the time series plots.

Response to Comment Item #7 (Flow under-predicted): A component was added to the model that allows for water losses upstream of Station #4. The addition of this component significantly improved model performance.

Response to Comment Item #8 (Under-predicting sediment): The model has since been recalibrated and performance of the SS component of the model has been significantly improved.

Response to Comment Item #9 (Baseflow dissolved arsenic is high for modules 3 and 8): Yes, the previous calibration and the current calibration provide for a high baseflow dissolved arsenic concentration from these 2 modules. It would be of interest to examine groundwater arsenic concentrations in the vicinity of the river to confirm the values used in the simulations. Some groundwater has been monitored upstream of Station 3 and such results indicate that arsenic groundwater concentrations are elevated in this area.

Summary/Recommendations

Response to Comment Item #1 (Sensitivity and Uncertainty Analysis): Sensitivity analysis has been included in the current report. Uncertainty analysis was not completed due to limitations in time and resources. In conversations with the model reviewer, a proper uncertainty analysis would require running the model tens of thousands of times. Time and resources were simply not available for such an analysis and thus only a sensitivity analysis is included in the current report.

Response to Comment Item #2 (Nash-Sutcliff coefficient of efficiency): It happens that the goodness of fit parameter, R^2, originally used is equivalent to the Nash-Sutcliff coefficient of efficiency and so this coefficient is used throughout to evaluate model performance.

Response to Comment Item #3 (Box plot of median, 25^{th} and 75^{th} percentile of observed data and model data for each Station): The 5, 10, 25, 50, 75, 90, and 95 percentile values are provided in tabular form within tables included in Section 5.0 and within tabular insets within Figure 5-1. Furthermore, histogram plots, which graphically show the frequency of occurrence of flow within different flow ranges, are also included as part of the model evaluation (Figure 5-1).

Response to Comment Item #4 (Use measured flow data): The model has since been updated by adding a component that allows for the loss of water immediately upstream of Station #4. This addition greatly improved the performance of the model in this area. A good alternative would have been to use the measured data at this station instead. One drawback of using the measured data, however, is that the data set is not 100% complete and values would have to have been estimated to fill the gaps. The addition of the new component that accounts for water loss has resulted in a significant improvement to the simulation which averted the need to substitute the modeled data with measured data at Station #4.

Response to Comment Item #5 (Describe how model parameters will be adjusted): The scenarios simulated along with the corresponding adjustment of parameters are described in the main text of the report (See Section 7.0 of the main report).